Springbank Off-Stream Reservoir Project Hydrology Flood Frequency Analysis

Report on Methods and Results

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Alberta Transportation

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Revision 1

December 14, 2015

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Executive Summary

Flood frequency analyses were performed for the Elbow River in Alberta for use in the design of the Springbank Off-stream Reservoir (SR1) project for the Province of Alberta. The results of the analyses will be utilized to establish hydraulic and structural design parameters, forecast frequency of project operation and develop operations guidelines.

The analyses were performed through a comprehensive evaluation of relevant recorded streamflow data for the Elbow River near the SR1 Diversion Site. Previous flood frequency studies were reviewed and an independent statistical flood frequency analysis was performed using conventional methods wherein the data was fit to ten probability distributions. Wide variability was observed in past efforts performed by others and the conventional methods performed by Stantec. This is attributed to the year to year variation in hydrometeorological processes (snowmelt, severe summer storms, etc.) that produce floods on the Elbow River. Additionally, the 2013 flood is an extraordinary flood with a peak discharge nearly double any flood in the last 108 years of observations.

Because of the mixed population of annual peak discharges and the presence of the extraordinary 2013 flood, an alternative approach to flood frequency analysis was adopted. The Unbiased Plotting Position Formulae for Historical Floods as described by Guo (1990) was used to calculate the return period for the extraordinary 2013 flood. Mathematic equations were then best fit to the series of flood values and their corresponding return periods.

Based on the presented methods, the 2013 flood event flood peak and volume are estimated to have a return period between 210 and 250 years. For the SR1 Diversion Site, the instantaneous peak discharge, 7-day volume and 56-day volume estimates are provided for floods having a return period between 2 and 500 years. The results are presented in Table E.1 below.

Table E.1 Estimated Flood Frequencies for the Elbow River at the SR1 Diversion Site

Return Period (years)	Instantaneous Peak Discharge (m^3/s)	7-Day Volume (dam^3)	56-Day Volume (dam^3)
500	1,800	174,000	371,000
200	1,110	132,000	322,000
100	765	107,000	290,000
50	530	86,600	260,000
20	330	65,600	226,000
10	200	53,100	203,000
5	140	38,100	172,000
2	70	20,000	105,000

1.0 INTRODUCTION

This report presents flood and volumetric frequency analysis methods and results that have been performed for the Elbow River relevant to the design of the Springbank Off-Stream Reservoir (SR1) project.

Previous flood frequency studies by AMEC (2014) and Golder (2010 and 2014) were reviewed. Stantec then performed an independent flood frequency analysis for a combined record from 1908 to 2013 using conventional methods. Finally, an alternative approach was reviewed to account for a mixed population data set and the presence of an extraordinary event within the data set.

The data, methods and results are presented in the following sections.

2.0 REVIEW OF PREVIOUS STUDIES

Previous studies performed by AMEC (2014) and Golder (2010 and 2014) were reviewed for applicability to the project. A summary of each study follows.

2.1 PRELIMINARY INFLOW DESIGN FLOODS FOR FLOOD CONTROL DAMS ON THE ELBOW AND BOW RIVERS (AMEC, 2014)

AMEC prepared a memo dated May 21, 2014 for the Southern Alberta Flood Recovery Task Force, reporting flood frequency analyses results. Several probability distributions and parameter estimation techniques were presented and tested. The results indicated that the Log Pearson Type III probability distribution with the method of moments for parameter estimation produced the best fit to the data. Flood and volumetric frequency analyses were performed for the Elbow River near Glenmore Reservoir using a combined hydrometric record of 1908 to 2013.

Several large historically observed floods occurred in 1879, 1897, and 1902 on the Bow and Elbow Rivers prior to the beginning of systematic hydrometric monitoring. Estimates of those historical flood peaks are available for the Bow River but not for the Elbow River. AMEC performed flood frequency analysis for the Bow River at Calgary using the 1911 to 2013 recorded data and also using a record length of 1879 to 2013 incorporating the historic data. Based on those analyses, a ratio of flood peaks for a given return period that ranged from 1 to 1.3 was determined. AMEC then performed flood frequency analyses for the Elbow River near Glenmore Reservoir using the combined record for 1908 to 2013. Those results are provided in Table 1 for the mean daily peak discharges and Table 2 for the instantaneous peak discharges. Based on previous flood frequency studies of both the Bow and Elbow Rivers, AMEC applied the ratios described above to the values in Table 1 and Table 2 to indirectly account for historic floods dating back to 1879. Notice that incorporating historic flood records increases the magnitudes of the 100-year to 1000-year flood peaks by 26% to 34%.

Table 1 Mean Daily Discharge Flood Frequency by Others Elbow River near Glenmore Reservoir, in m³/s

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)	Golder 2010 (1908 – 2008)	Golder 2014 (1908 – 2013)
1000	812	1013	766	1180
500	686	858	632	885
200	537	665	481	602
100	438	539	385	448
50	350	423	302	331
20	248	289	211	218

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)	Golder 2010 (1908 – 2008)	Golder 2014 (1908 – 2013)
10	182	202	154	156
5	124	130	107	108
2	59	53	56	58

Table 2 Instantaneous Peak Flood Frequency by Others Elbow River near Glenmore Reservoir, in m^3/s

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)	Golder 2010 (1908 – 2008)	Golder 2014 (1908 – 2013)
1000	1480	1984	1030	2220
500	1230	1625	841	1770
200	933	1197	633	1250
100	737	930	501	954
50	564	695	389	708
20	372	440	267	454
10	252	286	193	307
5	155	168	132	194
2	57	57	67	85

AMEC performed similar Bow River flood frequency analyses for 7-day flood volumes using data from 1908 to 2013 and historic data for pre-1908. AMEC then performed 7-day volumetric analyses for the Elbow River which were modified to account for the historic floods since 1879. The 7-day flood volume frequency results are presented in Table 3.

Table 3 7-Day Volume Flood Frequency by Others Elbow River near Glenmore Reservoir, in dam³

Return Period (years)	AMEC 2014 (1908 – 2013)	AMEC 2014 (1879 – 2013)
1000	176,256	206,659
500	155,520	183,139
200	130,464	152,203
100	112,320	130,640
50	95,040	109,523
20	74,131	83,049
10	59,270	63,987
5	44,928	46,369
2	26,179	24,104

2.2 HYDROLOGY STUDY, BOW AND ELBOW RIVER UPDATED HYDRAULIC MODEL PROJECT (GOLDER, 2010)

Golder prepared a report dated March 2010 for Alberta Environment (AENV) in cooperation with the City of Calgary, which provided results of flood frequency analyses. Golder used the 3-parameter Log Normal, Log Pearson Type III, and Extreme Value Type II probability distributions. They selected the final results from the Extreme Value Type II probability distribution. The purpose of the study was to provide peak flow estimates for delineation of flood hazards on the Bow River through Calgary. Flood frequency analyses were performed for the Elbow River inflow to Glenmore Reservoir and downstream of the reservoir for which Golder used the period of record 1908 to 2008. Those results are presented in Table 1and Table 2. Golder incorporated historic flood data for the Bow River into those analyses but did not make adjustments to the flood frequency results for the Elbow River for historic flood data.

The Golder 2010 report is of limited value to the SR1 project since it does not include the 2013 flood in the database. However, it is of interest in that it provides an estimate of flood frequency for the Elbow River prior to the occurrence of the 2013 flood.

2.3 BASIN-WIDE HYDROLOGY ASSESSMENT AND 2013 FLOOD DOCUMENTATION (GOLDER, 2014)

Golder prepared a report dated September 2014 for the City of Calgary in partnership with the Alberta Environment and Sustainable Resource Development (ESRD) to update the 2010 to 2012 Bow and Elbow River Hydraulic Model and Flood Inundation Mapping Project. The magnitude of the 2013 flood in the Bow and Elbow Rivers warranted a re-analysis of the flood frequency statistics presented in the Golder 2010 report.

Golder used the Environment Canada Consolidated Frequency Analysis (CFA) procedure. The results for the Elbow River near Glenmore Dam and for the Elbow River at Bragg Creek are presented in Table 2 and Table 4, respectively.

Table 4 Flood Frequency for the Elbow River at Bragg Creek

Return Period (years)	Instantaneous Peak Golder 2014 (m^3/s)
1000	1780
500	1320
200	883
100	643
50	462
20	290
10	198
5	129
2	64

2.4 CONCLUSIONS

The review of past studies identified gaps in available information required for the design of SR1. None of the above referenced studies provided comprehensive analyses for both flood peak and flood volume for the Elbow River at Glenmore and at Bragg Creek as required to estimate flood recurrence intervals and characteristics at the SR1 Diversion Site.

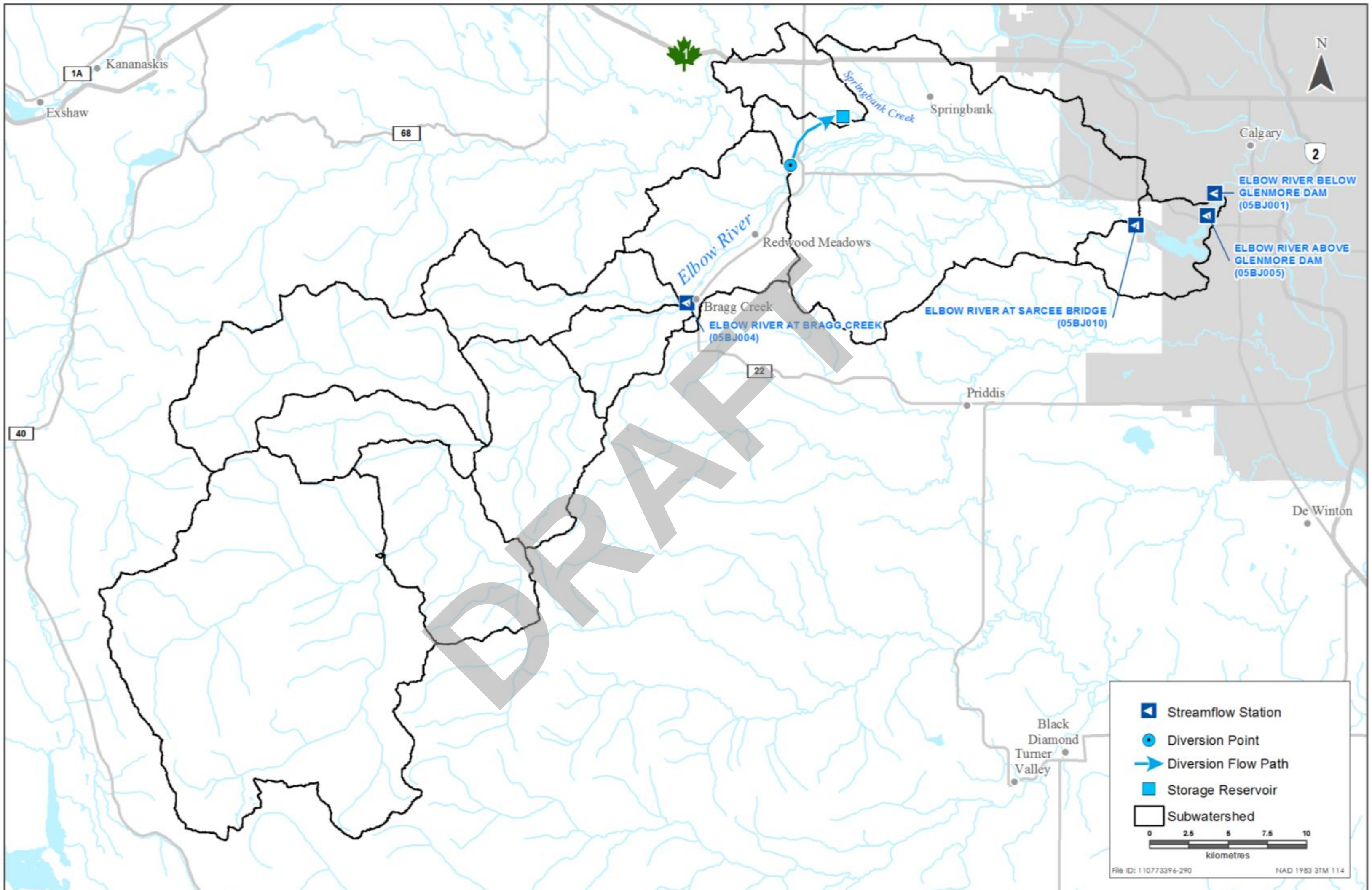
3.0 OBSERVED AND ESTIMATED PEAK FLOW AND VOLUME DATASET

3.1 HYDROMETRIC STATION RECORDS

Stantec identified seven hydrometric stations operated by Water Survey of Canada (WSC) within the Elbow River Basin. Hydrometric stations influenced by dam regulation (Glenmore Reservoir at Calgary (05BJ008)) or those having recorded data of less than 10 years (Little Elbow River above Nihahi (05BJ009)) were omitted from further analysis. The Elbow River station located above Elbow Falls (05BJ006) was also excluded from analysis due to its seasonal operation schedule and lack of relevant flow data (was discontinued in 1995). Therefore, the key gauging stations identified for analysis were Elbow River below Glenmore Dam (05BJ001), Elbow River at Bragg Creek (05BJ004), Elbow River above Glenmore Dam (05BJ005), and Elbow River at Sarcee Bridge (05BJ010). The Bragg Creek Station is located upstream of the proposed SR1 Diversion Site, while the remaining stations are situated downstream of the Diversion Site near the Glenmore Reservoir. See Table 5 and Figure 1 for a summary and figure of the relevant hydrometric stations.

Table 5 Relevant Hydrometric Station Summary

Station ID	Station Name	Drainage Area (km²)	Period of Record		Percent Missing Data	Years of Acceptable Flow Data	Type of Flow	Operation Schedule
			From	To				
05BJ001	Elbow River below Glenmore Dam	1235.7	1908	2011	2%	102	Unregulated (1908 – 1932)/ Regulated	Continuous
05BJ004	Elbow River at Bragg Creek	790.8	1934	2012	25%	59	Natural	Continuous
05BJ005	Elbow River above Glenmore Dam	1220	1933	1977	0%	45	Natural	Continuous
05BJ010	Elbow River at Sarcee Bridge	1189.3	1979	2012	37%	20	Natural	Continuous



Sources: Base Data - Natural Resources Canada. Thematic Data - Water Survey of Canada. Subbasin - Stantec Consulting Ltd. Project Data - Stantec Consulting Ltd.

Disclaimer: This map is for illustrative purposes to support this Stantec project; questions can be directed to the issuing agency.

Figure 1 Hydrometric Station Map

3.1.1 Combined Station

Stations on the Elbow River below Glenmore Dam, above Glenmore Dam, and at Sarcee Bridge have drainage areas of 1236, 1220, and 1189 km^2, respectively. Due to their proximity and similar drainage areas, their data was combined and considered as one station for further analysis (hereafter referred to as the Combined Station). The Combined Station consists of data from 1908 to 1932, 1934 to 1977, and 1979 to 2012, respectively. Only natural, unregulated flow is represented in the data series. Therefore, flow measurements up until the construction of the dam in 1934 were used at the station below Glenmore Dam. No flow data exists in 1933, 1978, and 1991 for any of the stations within the Combined Station grouping.

Annual maximum daily flows were recorded at the Combined Station for years prior to 1979. Peak instantaneous flows were first recorded at the Combined Station in 1979 and are available for most years between 1979 and the present.

Further, estimated annual maximum instantaneous peak flows for 23 additional years prior to 1978 were provided by the Province of Alberta for this location. These instantaneous peak flow estimates were first reported in a study titled Flood Protection – Elbow River Calgary (T. Blench & Associates Ltd, 1965) and have since been used by the Province for subsequent flood frequency estimates including the Calgary Floodplain Study (Alberta Environment 1983) and the Basin-Wide Hydrology Assessment and 2013 Flood Documentation (Golder, 2014).

3.1.2 Bragg Creek Station

Annual maximum daily flows were recorded at Bragg Creek for years prior to 1950. Peak instantaneous flows were first recorded at Bragg Creek in 1950 and are available for most years between 1950 and the present.

3.1.3 Observed Data Gaps

For the period of 1908 to 2013, the Combined Station is missing 2% and 54% of annual maximum daily and peak instantaneous flows, respectively. During the same period the Bragg Creek Station is missing 25% and 41% of annual maximum daily and peak instantaneous flows, respectively. The following sections describe the procedure for infilling missing annual maximum daily and peak instantaneous flows at Bragg Creek and the Combined Station for the flood frequency analyses.

3.2 JUNE, 2013 FLOOD EVENT

Due to damage during the June 2013 flood, official data from the gauging stations Elbow River at Bragg Creek and Elbow River at Sarcee Bridge was unavailable. However, Water Survey Canada (WSC) supplied preliminary 2013 peak instantaneous flows for the Elbow River at Bragg Creek and at Sarcee Bridge as 1150 and 1240 m^3/s, respectively (Lazowski pers. comm. 2015).

In addition, the City of Calgary provided an estimated inflow flood hydrograph into the Glenmore Reservoir for the June 2013 flood based on reservoir level and outflow analysis (see Figure 3). This estimated inflow into the Glenmore Reservoir was used to represent volume of flow at the Combined Station for the 2013 flood.

Real time preliminary water level data for Bragg Creek Station was then downloaded from WSC data server (note: these datasets did not undergo quality assurance and quality control practices by WSC). The WSC also supplied three stage-discharge rating curves (Curves 23, 24 and 25) for the Bragg Creek Station (Lazowski pers. comm. 2015). Curve 23 is applicable to data from January 1, 1998 to June 19, 2005. Curve 24 is fitted for use from June 19, 2005 to January 1, 2006. Curve 25 is related to data from January 1, 2006 and onward.

Stantec used Curves 24 and 25 in conjunction with the preliminary water level data at the Bragg Creek Station to estimate the 2013 flood hydrograph at Bragg Creek. Initially, Curve 25 was used to estimate the full 2013 flood hydrograph, as it was the latest developed curve. However, it appears Curve 25 overestimates the latter part of the falling limb of the 2013 hydrograph (from June 22, 2013 at 15:00 and on, when the stage was less than 3 m and the flow was less than 200 m^3/s). In comparison to the City of Calgary estimated inflow flood hydrograph into the Glenmore Reservoir, the flow at Bragg Creek was considerably greater for the latter part of the falling limb. When comparing Curve 24 to Curve 25, it was found that Curve 24 fit the lower flows better (see Figure 2). Therefore, Curve 25 was used from the beginning of the flood to June 22, 2013 at 15:00 and Curve 24 was used to estimate the remainder of the 2013 hydrograph.

Power equations were developed to fit the rating curve data provided by WSC for Curves 24 and 25. Both curves were fixed such that the maximum peak flow (Q = 1150 m^3/s, provided by WSC) occurred at the maximum level (h = 4.80 m on June 20, 2013 at 10:00, which was obtained from WSC real time stage data). The equations for the curves used to estimate the 2013 flood hydrograph at Bragg Creek are as follows:

$$Curve\ 24: Q = 24.45 \times (h - 0.8)^{2.91}$$

$$Curve\ 25: Q = 37.54 \times (h - 0.8)^{2.47}$$

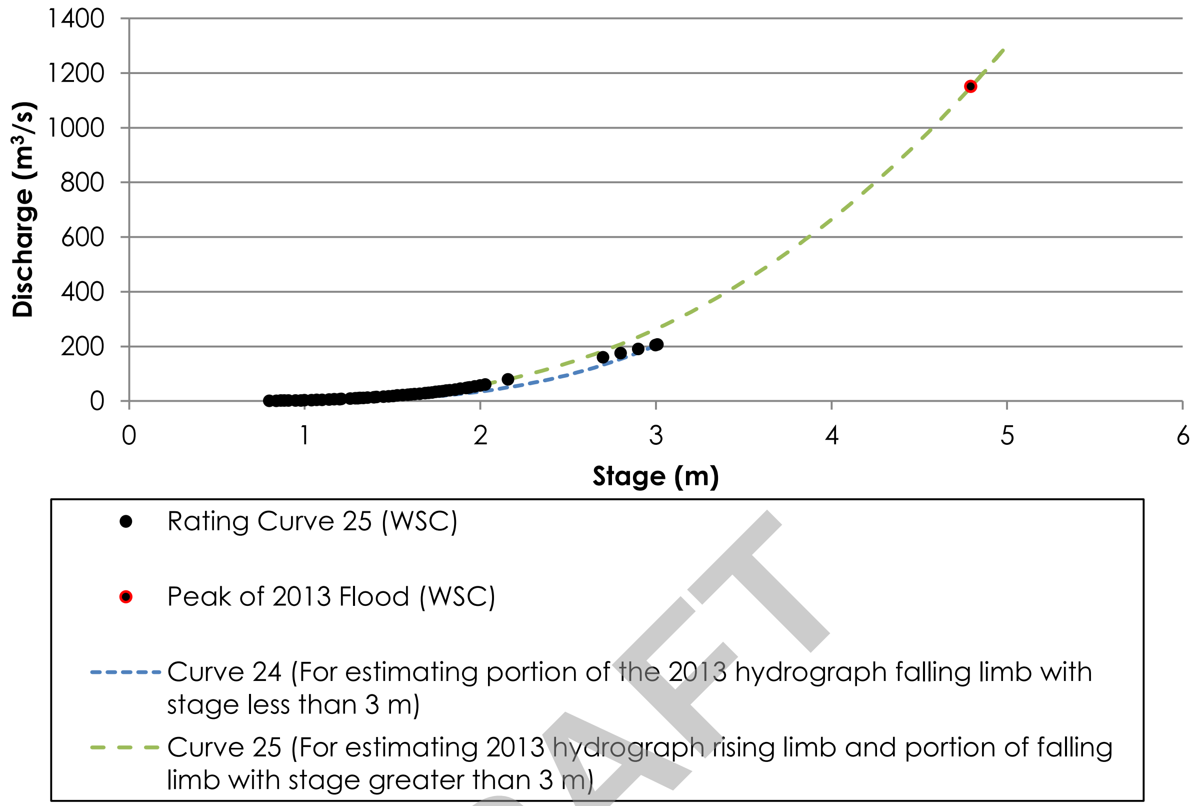


Figure 2 Rating Curves for Bragg Creek Station

Based on these two equations, Stantec generated an estimate of the June 2013 flow hydrograph at Bragg Creek (see Figure 3).

Although the WSC and City of Calgary preliminary values were used for analysis, it is important to note that they are estimates and are still under review by the WSC.

The hydrograph provided by ESRD for the Bragg Creek Station was used only as a comparison to the Stantec estimate and not for analyses. The ESRD and Stantec hydrographs at the Bragg Creek station had similar shapes but differed greatly in peak values. ESRD estimated the instantaneous peak "on the fly" to be 874 m^3/s at 13:14 on June 20, 2013, while WSC estimated the peak flow at approximately 1150 m^3/s at 10:00 on June 20, 2013.

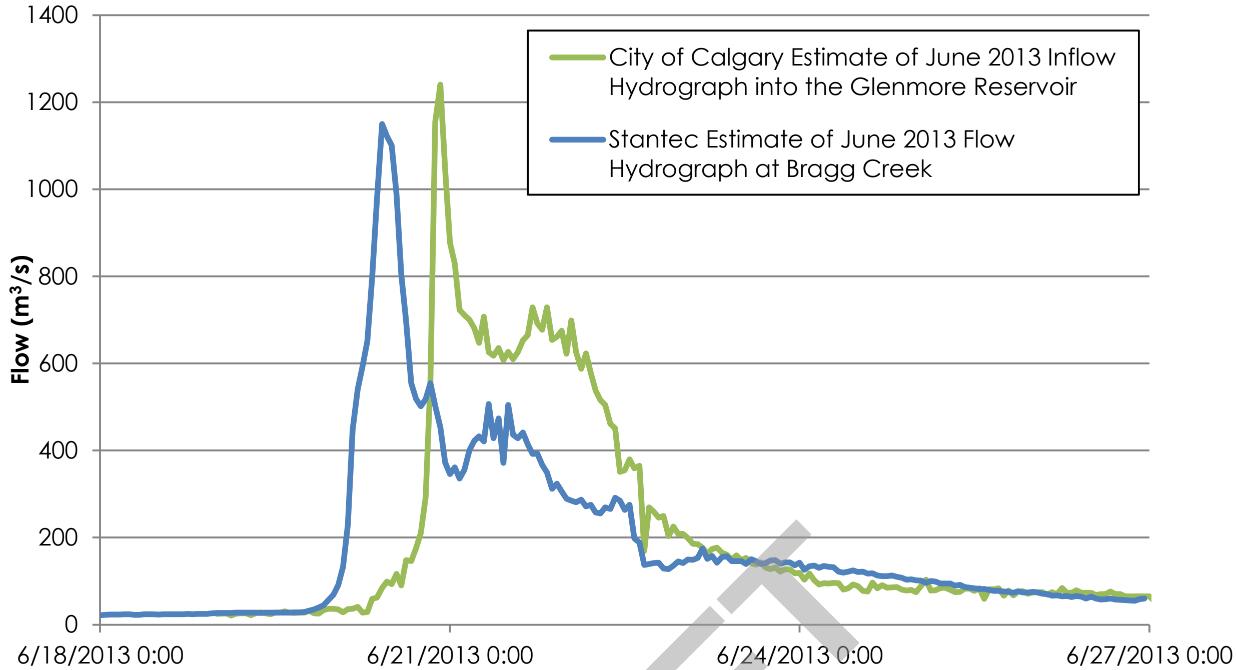


Figure 3 Preliminary 2013 Flood Hydrograph at Glenmore Reservoir and at Bragg Creek Station

The 7-day volume for 2013 the event was estimated based on the City of Calgary calculated inflow hydrograph into the Glenmore Reservoir (see Figure 3) at the Combined Station. This 2013 hydrograph covered a total of seven days, from June 20 to 26. The 2013 Bragg Creek 7-day flood volume also encompassed seven days, from June 20 to 26. It was calculated from the estimated 2013 flood hydrograph at Bragg Creek (see Figure 3).

The 56-day volume dataset did not include 2013 data since only nine days of flow data was available for analysis in 2013.

3.3 CORRELATION OF OBSERVED ANNUAL MAXIMUM DAILY FLOWS TO PEAK INSTANTANEOUS FLOWS

In order to perform comparable streamflow analyses, flow data pertaining to a common time period between the Bragg Creek and Combined Station was desired. Applying a common time period at both locations allowed for comparison of peak flows at the same plotting position. The annual maximum daily and peak instantaneous flow data were first recorded at the Combined Station in 1908 and 1979, respectively. The first record of annual maximum daily and peak instantaneous flow at Bragg Creek was 1935 and 1950, respectively. In order to carryout flow frequency analysis at both the Combined and Bragg Creek Stations using data from 1908 to 2013, an estimate was carried out to infill unrecorded and missing flow data. This was done by developing relationships between maximum daily and peak instantaneous flow at each station. See Table 5 for a description of the data at the WSC stations used for analysis.

3.3.1 Combined Station

A relationship between annual maximum daily and peak instantaneous flow was first developed at the Combined Station. Since peak instantaneous flow data was not recorded at the Elbow River below or above Glenmore Dam Stations, only data from Sarcee Bridge was used to build this relationship.

As stated previously, peak instantaneous flow data was not recorded at the Sarcee Bridge Station until 1979. Furthermore, there is no record of annual maximum daily flows for the years 1978 to 1989, 1991, and 1995 for the Sarcee Bridge Station. However, the complete daily hydrographs for those years, except 1978 and 1991, were available from WSC. Therefore, annual maximum daily flows for these years were taken from daily hydrograph data. In 2003 and 2007, the annual maximum daily flow occurred on a different day than the peak instantaneous flow of that year. For these two cases, annual maximum daily flow values were replaced by daily flow values with the same date as the peak instantaneous flow. Using the data described above, annual maximum daily and peak instantaneous flow data at Sarcee Bridge was analyzed from 1979 to 2013, excluding 1991, to represent the Combined Station (see Figure 4).

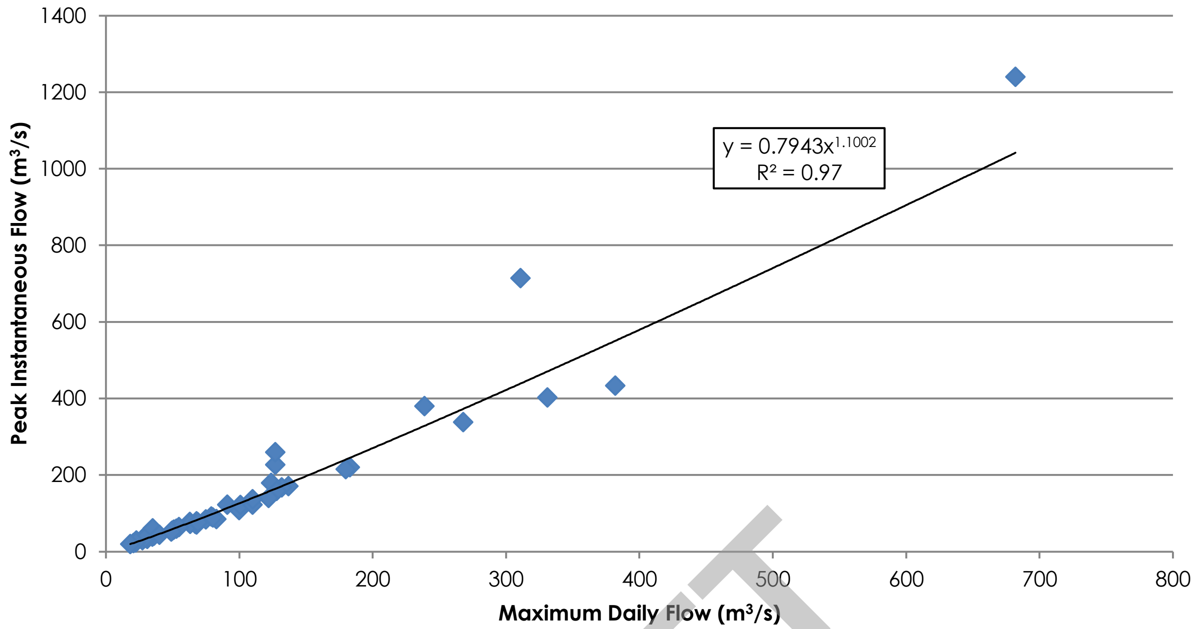


Figure 4 Relationship between Annual Maximum Daily and Peak Instantaneous Flow at the Combined Station.

The relationship in Figure 4 was used to estimate missing peak instantaneous flow records using annual maximum daily flows at the Sarcee Bridge Station. As annual maximum daily values were not recorded in 1978 or 1991 these values were estimated using the relationship between annual maximum daily values at the Bragg Creek and Combined Station (see Section 3.4).

3.3.2 Bragg Creek Station

Similar to the Combined Station, a relationship between annual maximum daily and peak instantaneous flows was developed at the Bragg Creek Station. As stated previously, peak instantaneous flow data was not recorded at the Bragg Creek Station until 1950. Therefore, annual maximum daily and peak instantaneous flow data at Bragg Creek was analyzed from 1950 to 2013.

Similar to the analysis completed at the Combined Station, the data was analyzed to omit flows that originated from different flood events for a particular year. Annual maximum daily flow values were replaced by daily flow values with the same date as the peak instantaneous flow for the years 1952, 1955, 1968, 1973, 1974, 1977, 1982, 1983, 2003, and 2012.

After review, the 1974 data was removed from analysis because of the uncharacteristically large difference between the values. The daily flow recorded on the same day as the peak instantaneous flow was 21 m³/s, while the peak instantaneous flow was 170 m³/s on average the peak instantaneous values were 23% greater than the maximum daily values for maximum daily flow values at Bragg Creek less than 100 m³/s. As a result the relationship at Bragg Creek was developed using data from 1950 to 1973 and 1975 to 2012 for a total of 62 years (see Figure 5).

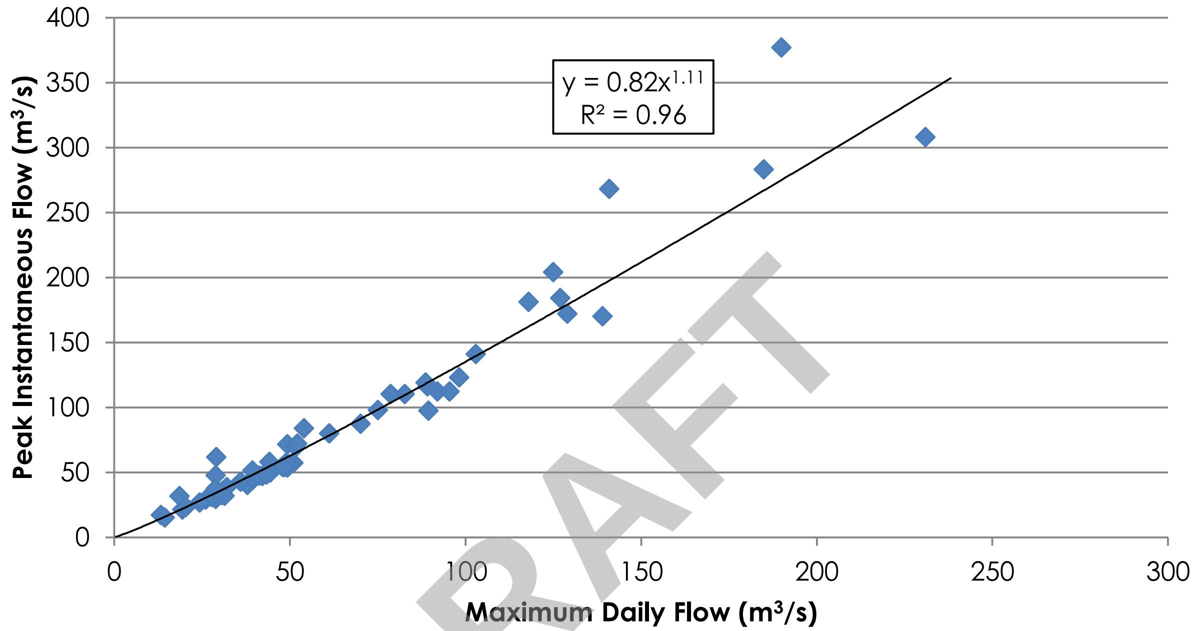


Figure 5 Relationship between Annual Maximum Daily and Peak Instantaneous Flow at the Bragg Creek Station

This relationship was used to estimate peak instantaneous flows for the period from 1908 to 1949 and 1993. As annual maximum daily values were not recorded until 1935, annual maximum daily values from 1908 to 1934 were estimated using the relationship between annual maximum daily values at the Bragg Creek and Combined Stations. The methodology for this relationship is explained in detail in Section 3.4.

3.4 CORRELATION OF OBSERVED FLOOD FLOW AND VOLUMES BETWEEN THE COMBINED AND BRAGG CREEK STATIONS

3.4.1 Annual Maximum Daily Flow Relationship between the Combined and Bragg Creek Stations

The first annual maximum daily record at the Bragg Creek Station was in 1935. To infill the record at Bragg Creek for years prior to 1935, a relationship between the annual maximum daily flows at the Bragg Creek and Combined Station was developed using the corresponding records from 1935 to 2012, excluding 1978 and 1991 as no annual maximum daily flow values were available at the Combined Station. Therefore, the relationship was created using data from 1935 to 1977, 1979 to 1990, and 1992 to 2012; for a total of 76 years. See Figure 6 for this relationship.

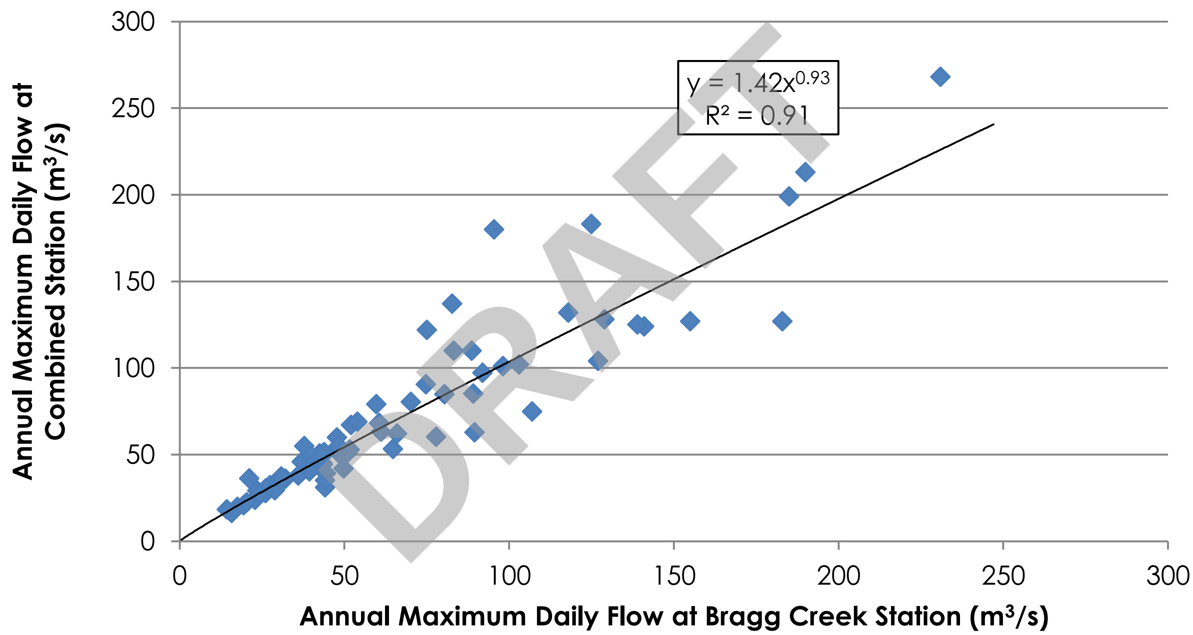


Figure 6 Relationship between Annual Maximum Daily Flow at the Bragg Creek and Combined Stations

3.4.2 Annual Maximum 7-Day and 56-Day Volume Relationship between the Combined and Bragg Creek Stations

Volumetric frequency analysis was carried out for two different time periods of 7- and 56-day duration. In order to calculate the volume of water, moving sums of daily flow were performed for consecutive durations of 7- and 56-day periods at the Combined and Bragg Creek Stations. From this data, the annual maximum 7- and 56-day volumes were identified.

Daily discharge data is available from 1908 to 2012 at the Combined Station. However, the first record of daily flow data at the Bragg Creek Station was in 1934. Therefore, annual maximum 7- and 56-day volumes at the Bragg Creek Station were not available from 1908 to 1933. In order to estimate the 7- and 56-day volumes at Bragg Creek for the period of 1908 to 1933, a relationship was created between the Bragg Creek and Combined Stations based on a time period where data exists for both stations. The 7-day volume relationship was based on data from 1934 to 2013, excluding 1978 and 1991. The 56-day volume relationship was built on data from 1934 to 2012, excluding 1978 and 1991.

The Bragg Creek Station volumes from 1908 to 1933 were then estimated using the relationship between the two stations 7- and 56-day volumes (see Figure 7 and Figure 8). Therefore, 25% of the 7- and 56-day volumes at the Bragg Creek Station were estimated.

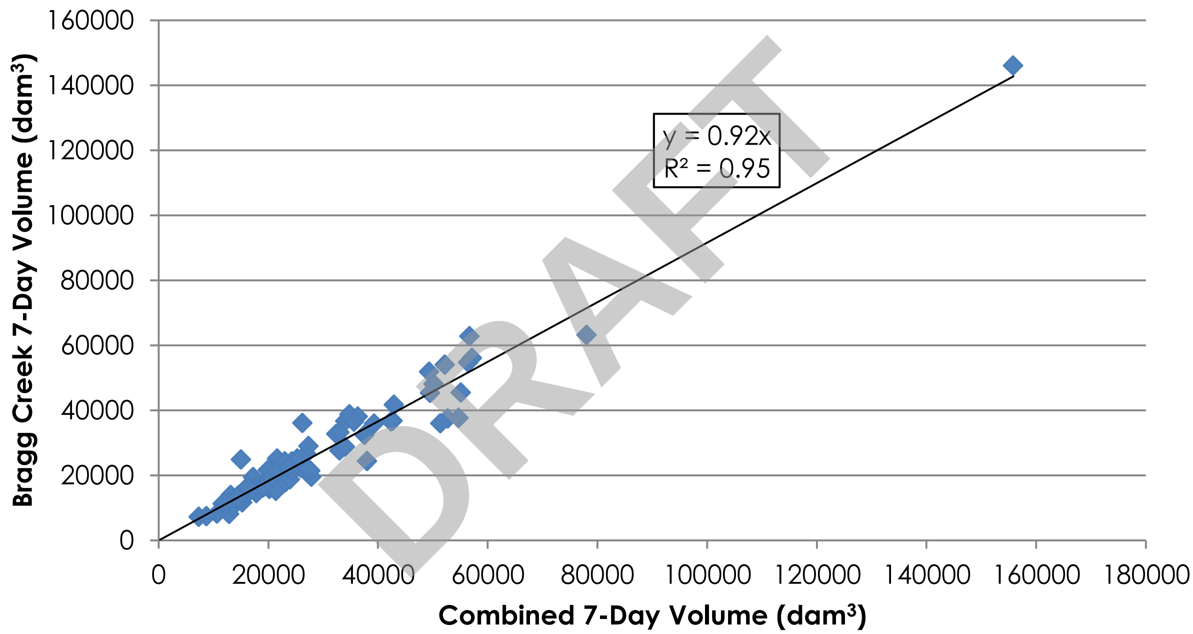


Figure 7 Annual Maximum 7-Day Volume Relationship between the Bragg Creek and Combined Stations (1934 – 2013), in dam³

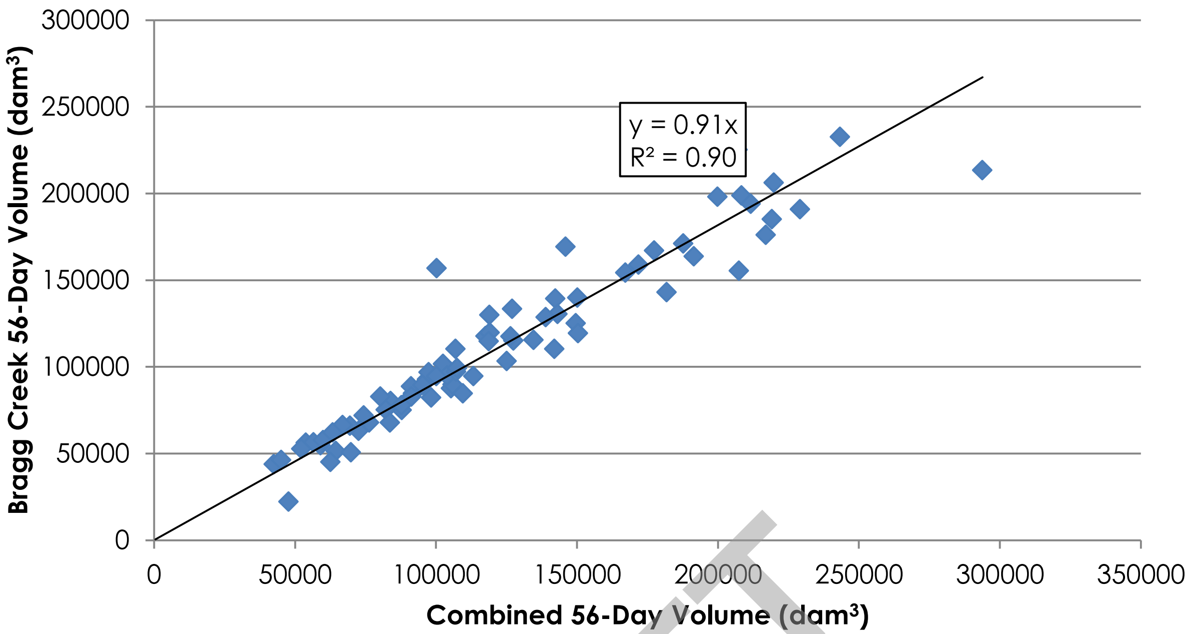


Figure 8 Annual Maximum 56-Day Volume Relationship between the Bragg Creek and Combined Stations (1934 – 2012), in dam3

3.5 CONSTRUCTED DATASETS FOR PEAK FLOW AND VOLUME

Stantec developed a combined record of peak flow and flood volume estimates for the period of 1908 to 2013 using the data and methods described in the previous sections. Tables presenting the observed and estimated values for annual maximum daily, peak instantaneous, 7-day volume and 56-day volume at both the Combined and Bragg Creek Stations are provided in Appendix A. Figures 9 and 10 show the full record of observed and estimated peak instantaneous flows for the Bragg Creek and Combined Stations.

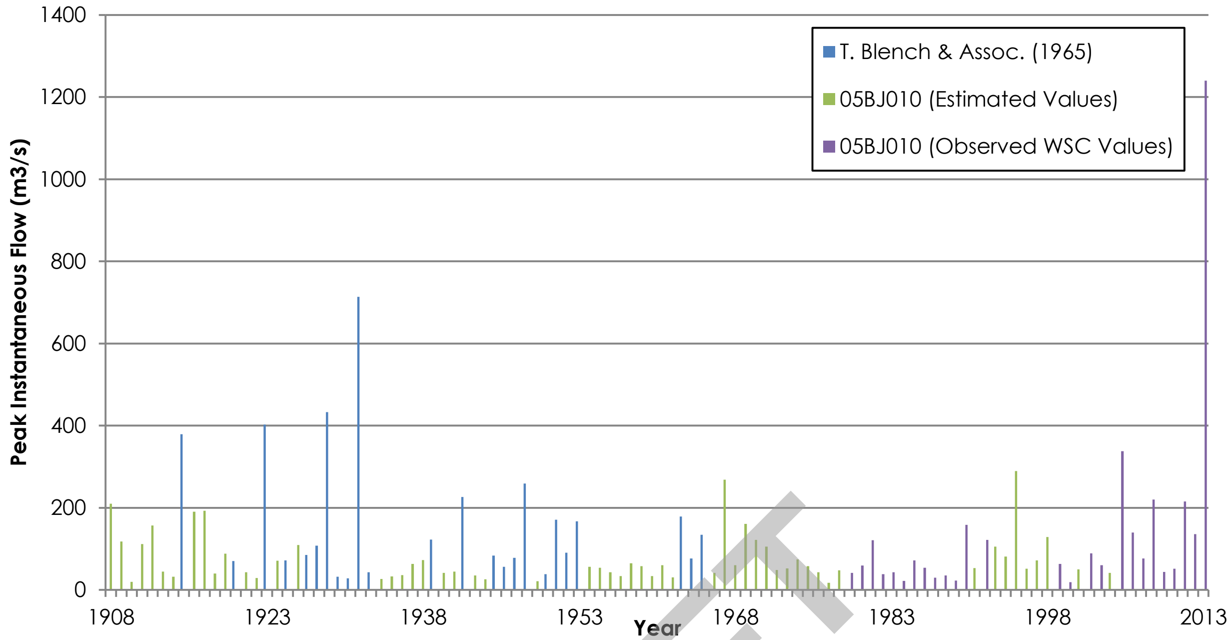


Figure 9 **Observed and Estimated Peak Instantaneous Flows of Elbow River at Combined Station (1908 – 2013)**

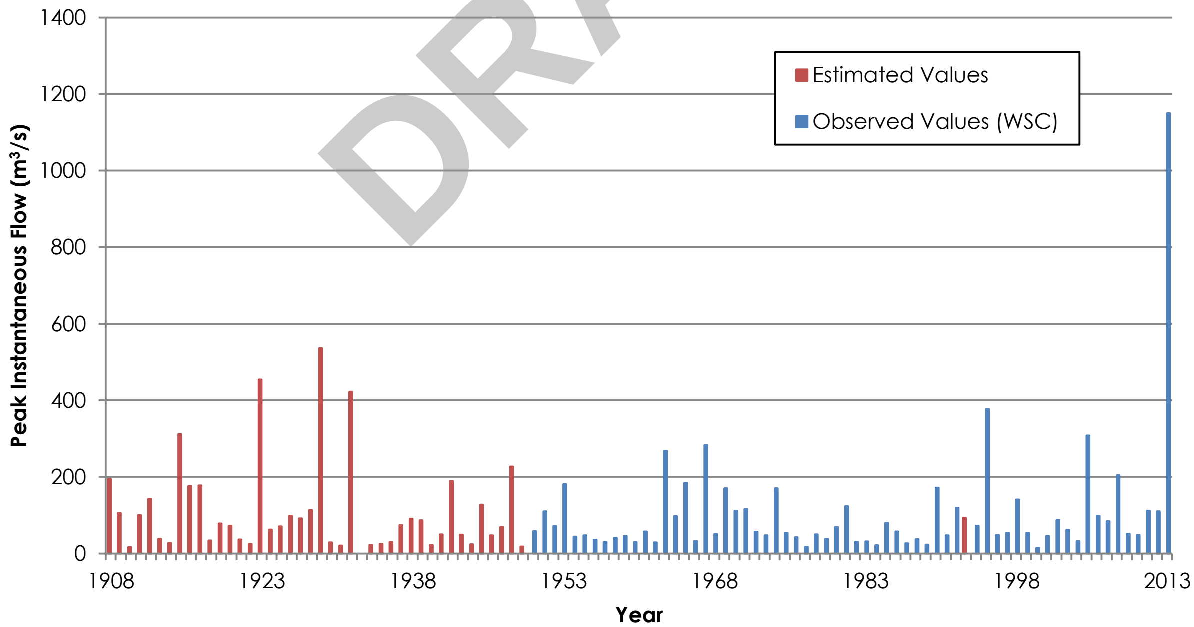


Figure 10 **Observed and Estimated Peak Instantaneous Flows of Elbow River at Bragg Creek Station (1908 – 2013)**

4.0 FLOOD PEAK AND VOLUMETRIC FREQUENCY ANALYSIS RESULTS

Flood peak and volumetric frequency analyses were conducted on six datasets:

1. Annual peak instantaneous flow at the Combined Station (1908 – 2013),
2. Annual peak instantaneous flow at the Bragg Creek Station (1908 – 2013),
3. Annual maximum 7-day volume at the Combined Station (1908 – 2013),
4. Annual maximum 7-day volume at the Bragg Creek Station (1908 – 2013),
5. Annual maximum 56-day volume at the Combined Station (1908 – 2012), and
6. Annual maximum 56-day volume at the Bragg Creek Station (1908 – 2012).

4.1 FREQUENCY ANALYSIS PROCEDURE

Flood peak and volumetric frequency analyses were carried out at the Combined and Bragg Creek Stations using ten different probability functions. Analysis methods generally followed the Frequency Analysis Procedure for Stormwater Design developed the City of Calgary (City of Calgary 2014). The Hydrologic Frequency Analysis Plus (HYFRAN+) software package was utilized to fit the statistical distributions to the data series. HYFRAN+ is a numerical tool that can be used to compare multiple frequency distributions and parameter estimation methods and perform goodness-of-fit and data series characteristic tests.

The following probability distributions were analyzed with the distribution parameter estimation methods listed in parentheses (MLE = maximum likelihood estimation, MOM = method of moments, and SAM = methodé SAM):

- Normal (MLE)
- Log Normal (MLE)
- Log Normal III (MLE)
- Exponential (MLE)
- Pearson III (MOM)
- Log Pearson III (SAM)
- Gumbel (MLE)
- GEV (MLE)
- Weibull (MLE)
- Gamma (MLE)

Prior to fitting the appropriate curve, a variety of statistical tests were performed to determine the quality of the input data using the City of Calgary's spreadsheet tool (Calgary, 2014). These tests evaluate the dataset for randomness, stationarity, homogeneity, independence and the presence of outliers. A summary of the test results is provided in Table 6. The tests identified potential issues with each of the six constructed datasets to be analyzed.

The results of the ten probability functions analyzed produced wide varying results and did not provide a sufficient representation for the full data set upon visual inspection. As such, a different methodology was selected and is described in the next section.

Table 6 Statistical Characteristics of Flood Peak and Volumetric Frequency Datasets

Statistical Tests		Peak Instantaneous Flow (1908 - 2013)		Maximum 7-Day Volume (1908 - 2013)		Maximum 56-Day Volume (1908 - 2012)	
		Combined Station	Bragg Creek Station	Combined Station	Bragg Creek Station	Combined Station	Bragg Creek Station
Stationarity	Spearman Rank Order Correlation Coefficient (Trend)	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05	no significant trend at a=0.05
	Mann-Whitney Test for Jump	no jump at a=0.05	no jump at a=0.05	no jump at a=0.05	presence of jump possible at a=0.05	no jump at a=0.05	no jump at a=0.05
	Wald-Wofowitz Test (Jump)	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05	presence of jump possible at a=0.05
Homogeneity	Mann-Whitney U Test	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05
	Terry Test	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05	sample is homogenous at a=0.05
Independence	Spearman Rank Order Correlation Coefficient	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05	sample is independent at a=0.05
	Wald-Wolfowitz Test for Independence	sample is independent at a=0.05	sample is independent at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05
	Anderson Test	sample is independent at a=0.05	sample is independent at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05	non-independence detected at a=0.05
Outliers	Grubbs and Beck Test	high outlier may be present; no low outliers	high outlier may be present; no low outliers	no high outliers; no low outliers	no high outliers; no low outliers	no high outliers; no low outliers	no high outliers: low outlier may be present

4.2 UNBIASED METHOD

As discussed above, traditional flood frequency methods provide a wide range of values for the same exceedance probability. Furthermore, multiple statistical tests were violated for each of the flood peak and volumetric datasets. Limited confidence is warranted for methods that fit the Elbow River hydrometric data to single preordained mathematical probability distributions by statistical methods. This appears related to two factors: first, floods on the Elbow River are from a mixed population of snowmelt, spring rain on snow, and summer rainfall only floods. Therefore, no single probability distribution can be expected to fit the data. Second, the 2013 flood was an exceptional hydrologic event. There is no other recorded flood on the Elbow River that is represented by the 2013 flood in regard to peak discharge, flood volume, or runoff response time (hydrograph shape).

To properly account for the extraordinary 2013 flood, the Unbiased Plotting Position Formulae for Historical Floods as described by Guo (1990) was used. This method accounts for the extraordinary floods by calculating the plotting position for that event as follows:

$$P_e = \left(\frac{m - 0.4}{k + 0.2}\right)\left(\frac{k}{N}\right) \ for\ m = 1, \dots, k$$

$$P_e = \frac{k}{N} + \left(\frac{N - k}{N}\right)\left(\frac{m - k - 0.4}{N - k + 0.2}\right)\left(\frac{N - k}{N_s - e}\right) \ for\ m = k + 1, \dots, N_g$$

Where:

- P_e = the probability of exceedance,
- m = the rank of each flood event (from 1 to N_g) in descending magnitude order,
- N = the effective record length,
- N_s = the number of years in the systematic record,
- e = the number of extraordinary floods in the systematic record,
- k = the number of historic plus extraordinary floods, ($h + e$, where h is the number of historic data),and
- N_g = the number of systematic record plus historic data ($N_s + h$, where h is the number of historic data).

For the peak instantaneous flow datasets at the Bragg Creek and Combined Stations the value of N was 106, as the data ranged from 1908 to 2013. A k value of 1 was used because there was one extraordinary flood (the 2013 flood) and no historic floods were considered in this analysis (h = 0).

The instantaneous peak discharges and corresponding probability of exceedance were plotted on log-log paper and best fit lines were mathematically calculated to those data points. A logarithmic equation was found to best fit data with a return period less than the 10 years. For data with return periods greater than 10 years, a power equation was found to best fit the data. The graphical flood peak data analysis for the Combined Station is shown in Figure 11 and for the Bragg Creek Station in Figure 12. From these relationships, Stantec estimated the 5-, 10-, 20-, 50-, 100-, 200-, and 500-year flood peaks as presented in Table 7. The results from this method are used for further analysis and evaluations. Instantaneous peak values are reported to the nearest 5 m^3/s.

Table 7 Flood Peak Frequency Results using Unbiased Method (1908 – 2013)

Return Period (years)	Instantaneous Peak Discharge (m^3/s)	
	Combined	Bragg Creek
500	2,035	1,745
200	1,215	1,085
100	820	755
50	560	525
20	330	330
10	205	200
5	145	140
2	70	70

For the 7-day volumetric analysis, a N value of 106 was used, as the frequency analysis was conducted on data from 1908 to 2013. The value of k was 1 since there was one extraordinary flood (the 2013 flood, e = 1) and no historic floods were considered (h = 0).

The 7-day flood volumes and corresponding probability of exceedance were plotted on log-log paper and best fit lines were mathematically calculated to those data points. A logarithmic equation was found to best fit data with a return period less than the 10-years. For data with return periods greater than 10-years a power equation was found to best fit the data. The graphical 7-day flood volume data analysis for the Combined Station is shown in Figure 13 and for the Bragg Creek Station in Figure 14. From these relationships, Stantec estimated the 5-, 10-, 20-, 50-, 100-, 200-, and 500-year 7-day flood volume as presented in Table 8. The 7-day volumes are rounded to 3 significant figures.

Table 8 7-Day Volumetric Frequency Results using Unbiased Method (1908 – 2013)

Return Period (years)	7-Day Volume (dam^3)	
	Combined	Bragg Creek
500	192,700	170,000
200	146,000	129,000
100	119,000	105,000
50	96,000	85,400
20	73,000	64,900
10	59,700	52,700
5	41,300	37,300
2	21,500	19,700

For the 56-day flow volumes at the Bragg Creek Station and the Combined Station the value of N was 105, as the data ranged from 1908 to 2012. Since there was no 56-day data for the 2013 flood there are no extraordinary floods in the data set. The Unbiased Method formula for a data set with extraordinary flood events (or outliers) follows the Cunnane plotting position formula:

$$P_e = \left(\frac{m - 0.4}{N + 0.2}\right)$$

Where:

- P_e = the probability of exceedance,
- m = the rank of each flood event (from 1 to N) in descending magnitude order, and
- N = the effective record length.

The 56-day flood volumes and corresponding probability of exceedance were plotted on log-log paper and best fit lines were mathematically calculated to those data points. A logarithmic equation was found to best fit data with a return period less than the 10-years. For data with return periods greater than 10-years a power equation was found to best fit the data. That graphical 56-day flood volume analysis for the Combined Station is shown in Figure 15 and for the Bragg Creek Station in Figure 16. From these relationships we were able to estimate the 5-, 10-, 20-, 50-, 100-, 200-, and 500-year 56-day flood volumes as presented in Table 9. The 56-day volumes are rounded to 3 significant figures.

Table 9 56-Day Volumetric Frequency Results using Unbiased Method (1908 – 2012)

Return Period (years)	56-Day Volume (dam³)	
	Combined	Bragg Creek
500	420,800	358,000
200	360,700	312,000
100	321,000	282,000
50	285,700	254,000
20	245,000	221,000
10	238,000	199,000
5	184,000	169,000
2	112,000	103,000

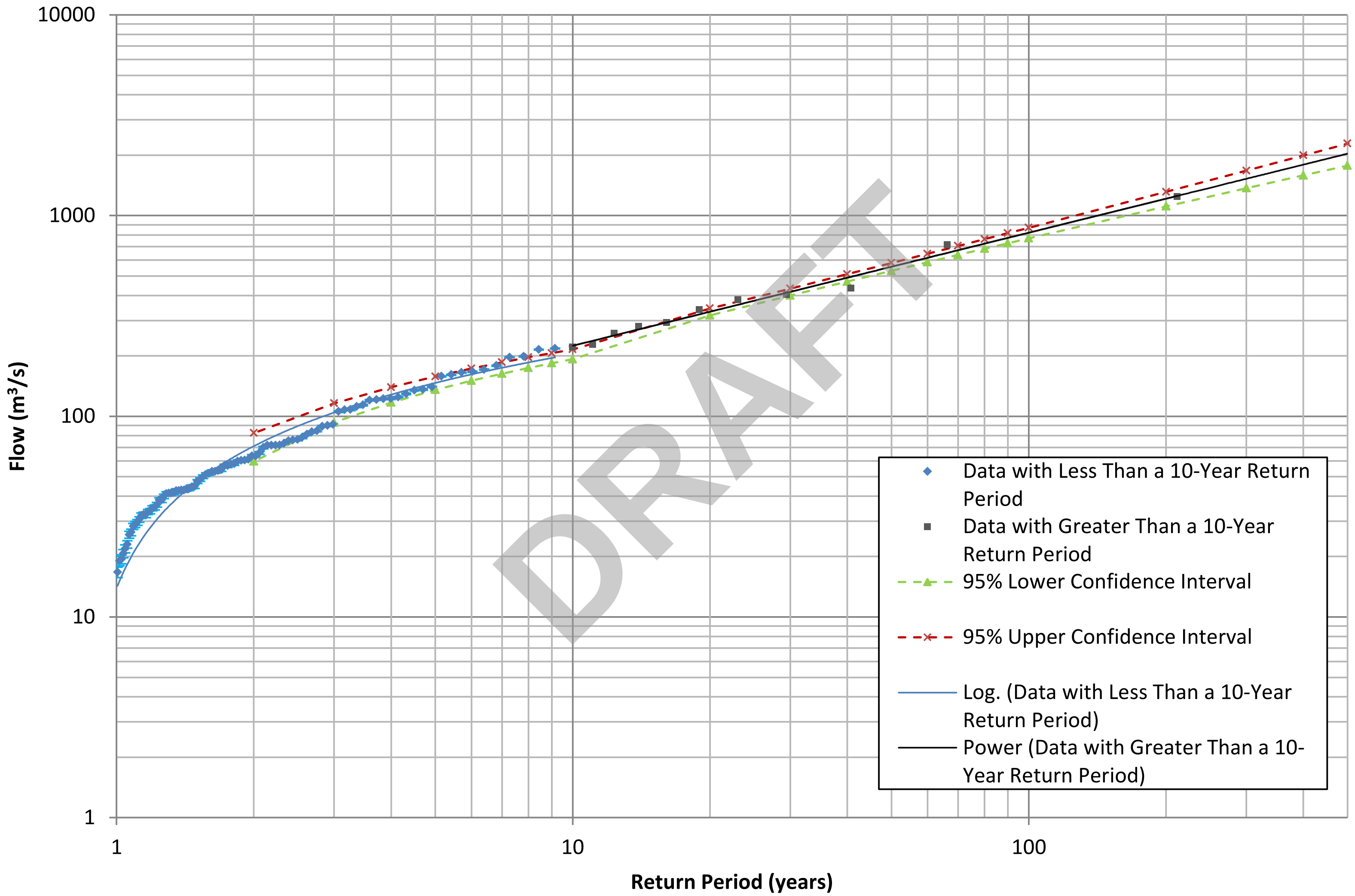


Figure 11 Graph of Elbow River at the Combined Station Flood Peak Frequency Results using Unbiased Method (1908 – 2013)

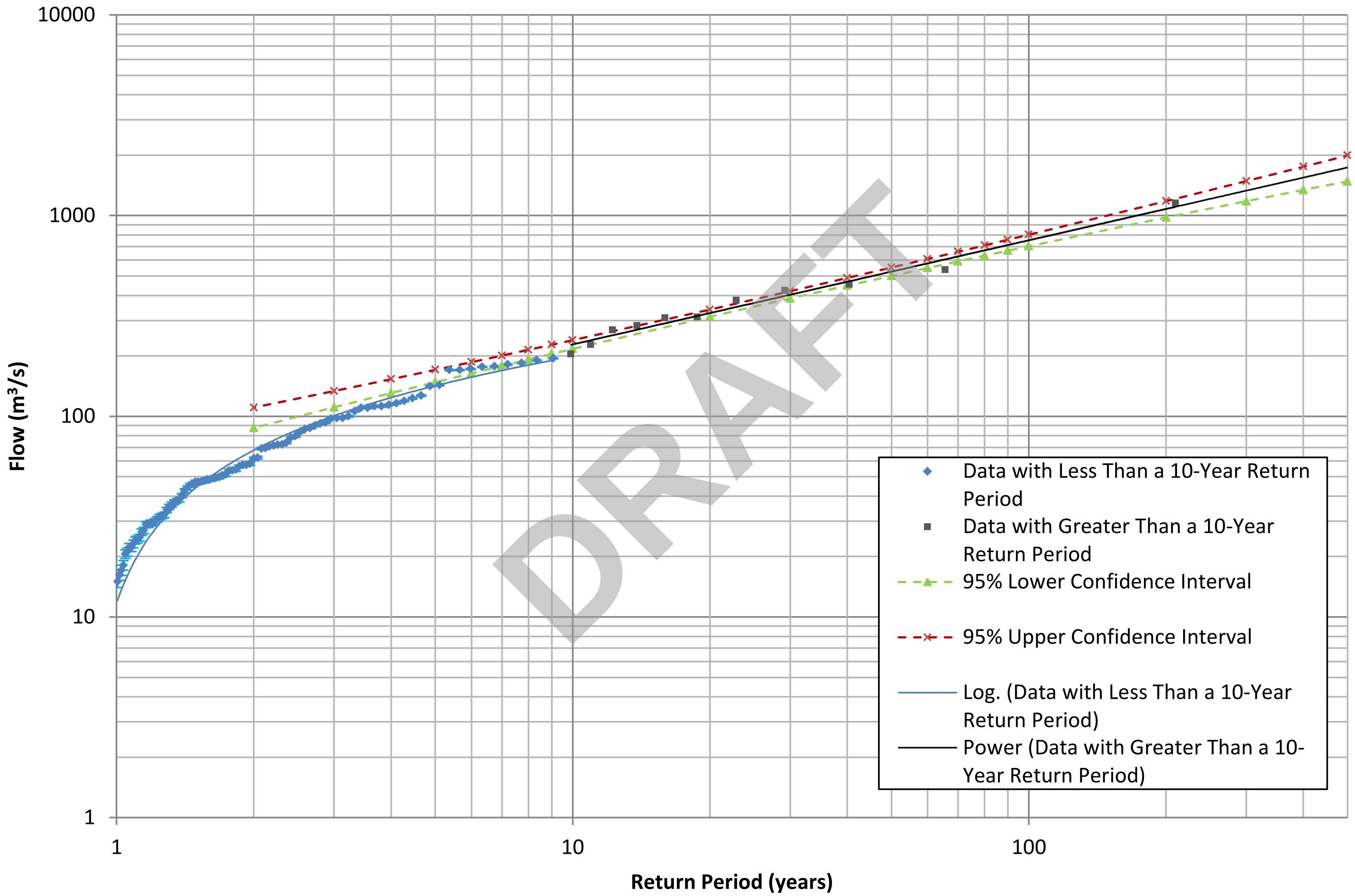


Figure 12 Graph of Elbow River at the Bragg Creek Station Flood Peak Frequency Results using Unbiased Method (1908 – 2013)

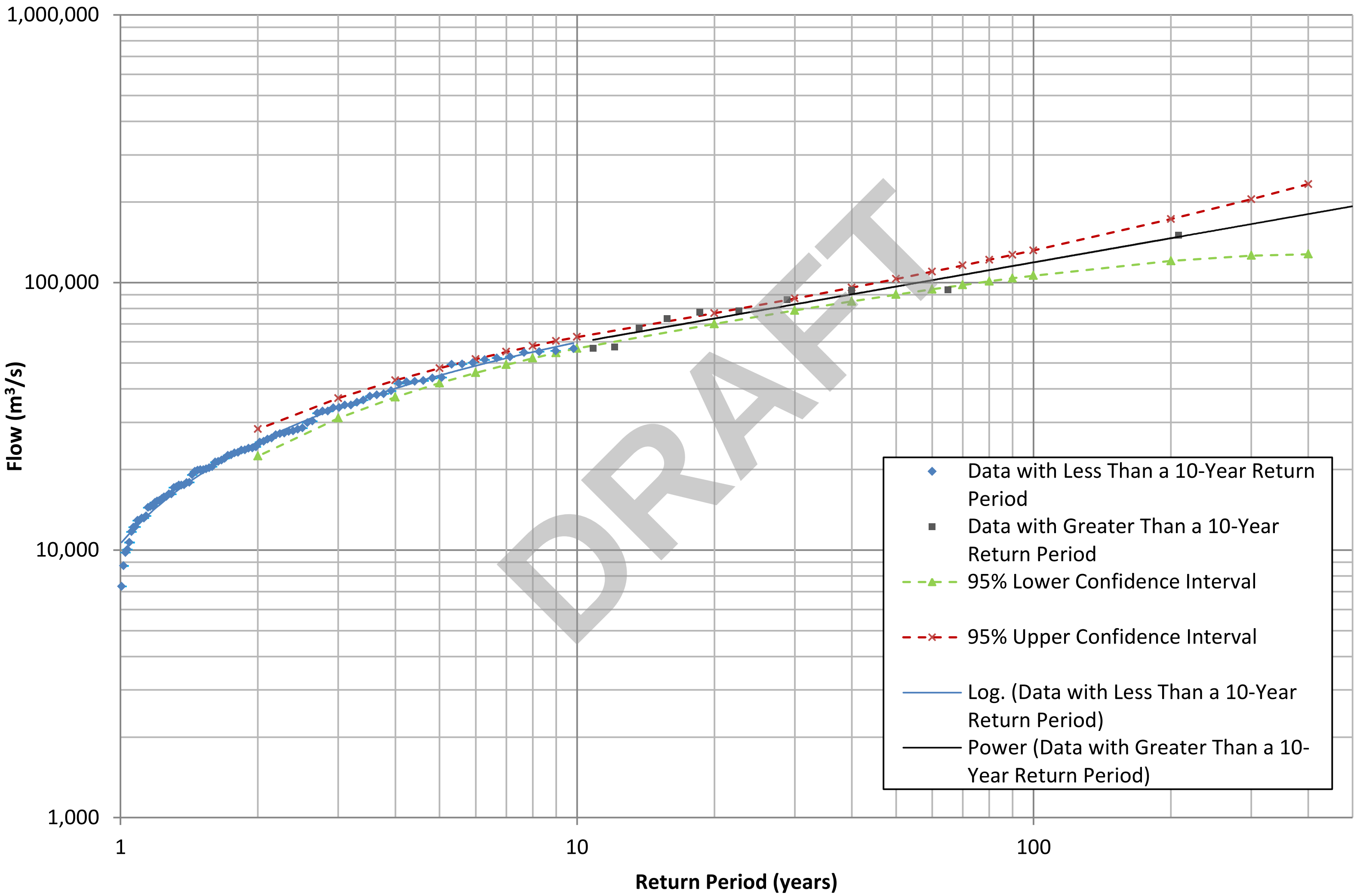


Figure 13 Graph of Elbow River at the Combined Station 7-Day Volumetric Frequency Results using Unbiased Method (1908 – 2013)

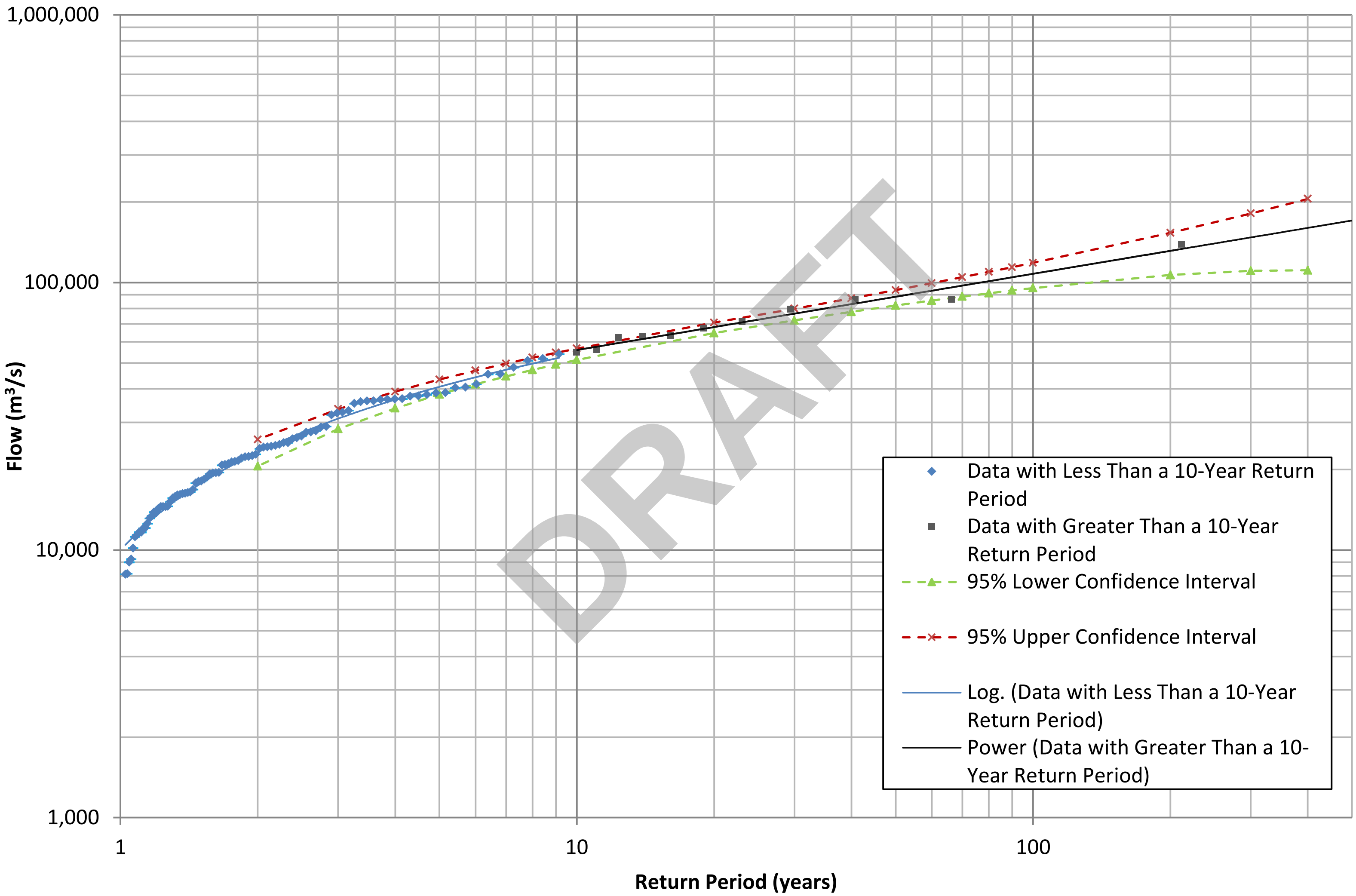


Figure 14 Graph of Elbow River at the Bragg Creek Station 7-Day Volumetric Frequency Results using Unbiased Method (1908 – 2013)

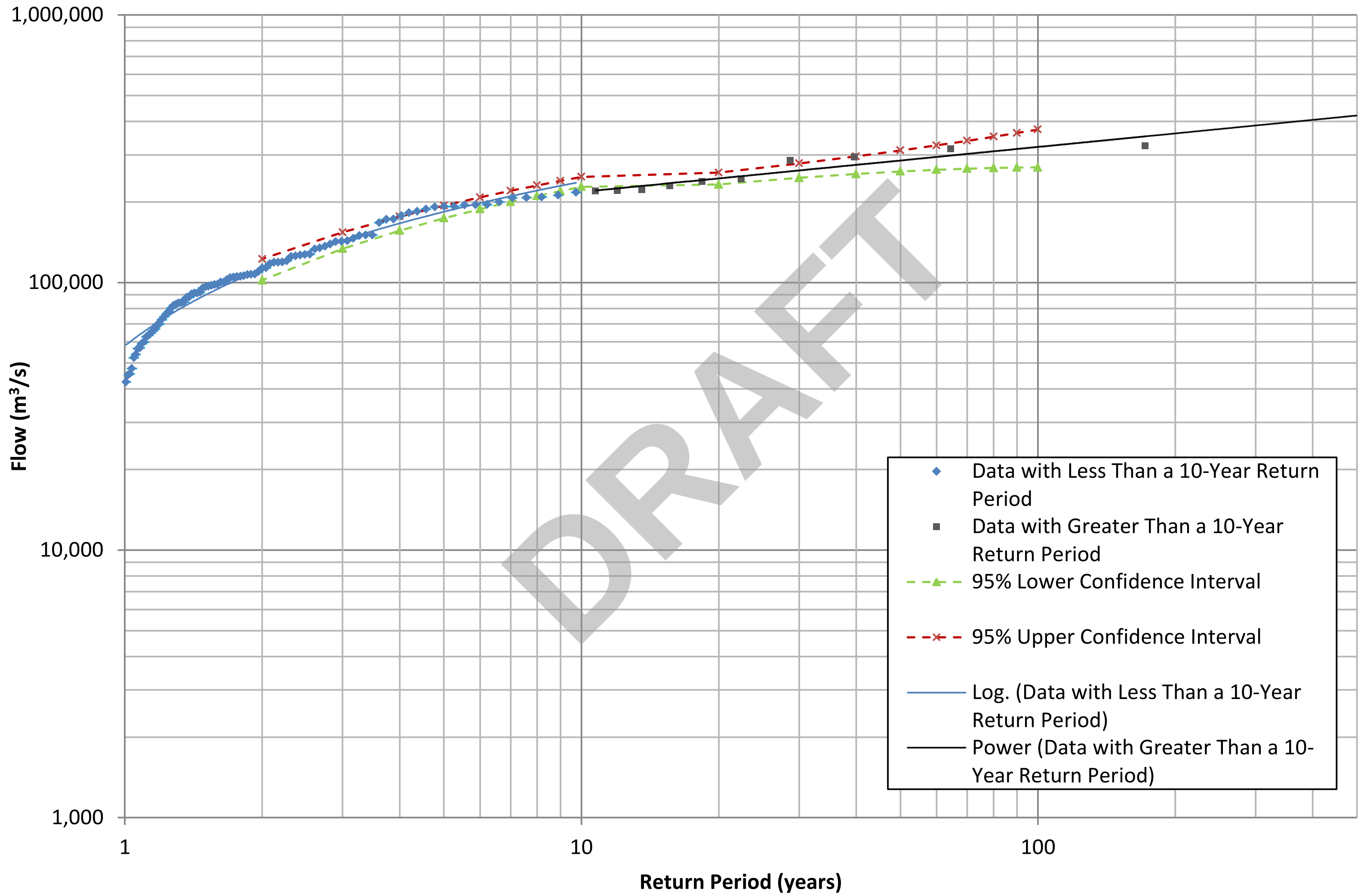


Figure 15 Graph of Elbow River at the Combined Station 56-Day Volumetric Frequency Results using Unbiased Method (1908 – 2012)

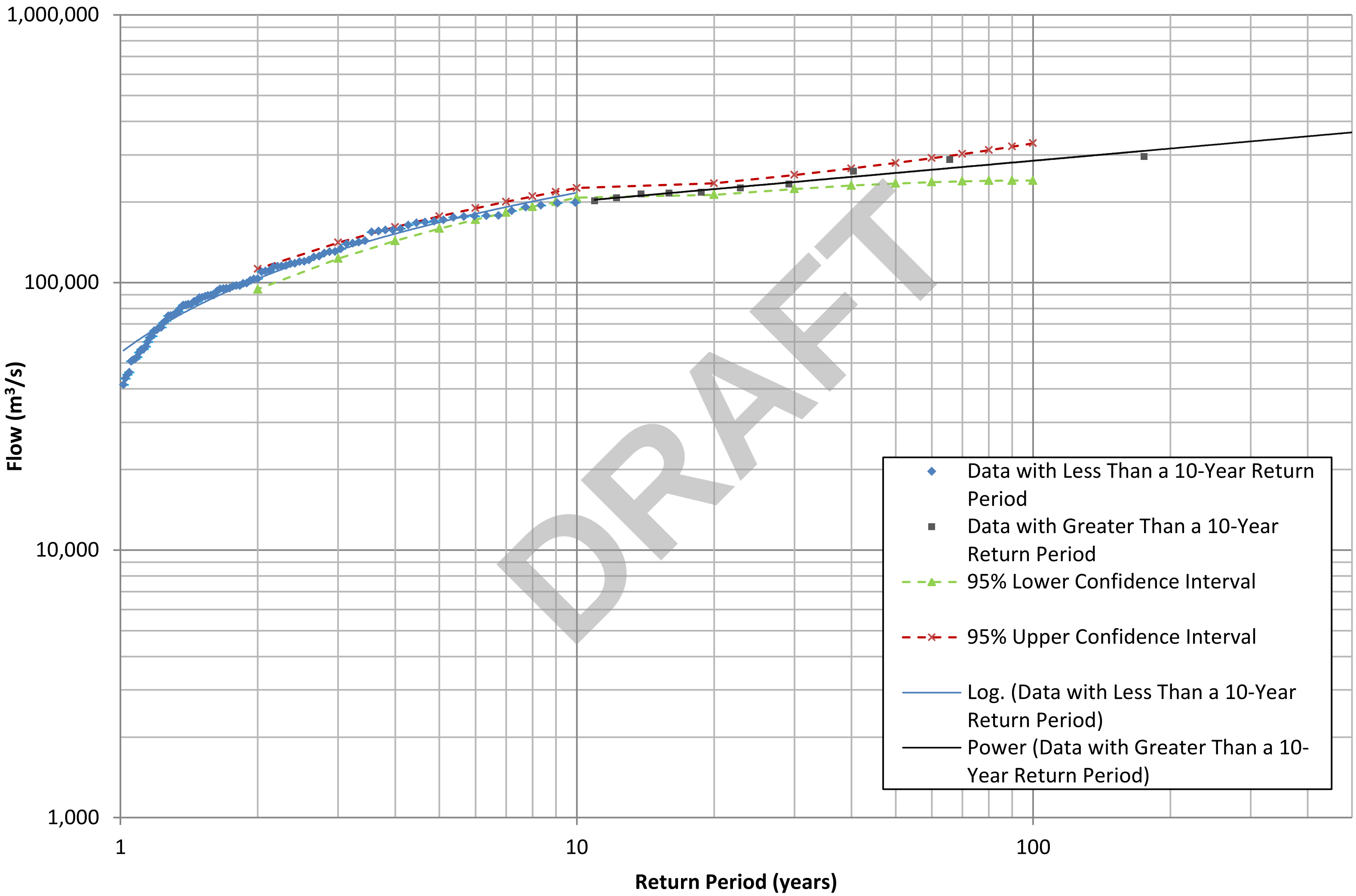


Figure 16 Graph of Elbow River at the Bragg Creek Station 56-Day Volumetric Frequency Results using Unbiased Method (1908 – 2012)

The equations for the best fit lines to the data points in Figure 11 through Figure 16 are provided in Table 10.

Table 10 Equation of the Best Fit Lines for the Combined and Bragg Creek Stations Flood and Volumetric Frequency Results using the Unbiased Method

Location	Instantaneous Peak Flood Frequency				7-Day Volumetric Frequency				56-Day Volumetric Frequency			
	Less than 10-Year Return Period		Equal to or Greater Than 10-Year Return Period		Less than 10-Year Return Period		Equal to or Greater Than 10-Year Return Period		Less than 10-Year Return Period		Equal to or Greater Than 10-Year Return Period	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
Combined Station	$Q = 82.55\ln T+13.82$	0.98	$Q = 61.37T^{0.57}$	0.99	$V = 21{,}366\ln T + 10554$	0.99	$V = 29{,}867T^{0.3}$	0.94	$V = 78{,}200\ln T + 58{,}000$	0.98	$V = 148{,}000T^{0.17}$	0.88
Bragg Creek Station	$Q = 81\ln T+11.62$	0.98	$Q = 69.03T^{0.52}$	0.98	$V = 19{,}100\ln T + 6{,}400$	0.99	$V = 26{,}400T^{0.30}$	0.97	$V = 71{,}900\ln T + 53{,}300$	0.98	$V = 141{,}100T^{0.15}$	0.94

Where Q = flow (m^3/s), V = volume (dam^3), and T = return period (years)

4.3 SUMMARY OF FLOOD FREQUENCY RESULTS

A summary of Stantec's flood frequency results using the Unbiased Method are presented in Table 11.

Table 11 Summary of Flood Frequency Results by Stantec

Return Period (years)	Instantaneous Peak Discharge (m^3/s)		7-Day Volume (dam^3)		56-Day Volume (dam^3)	
	Combined	Bragg Creek	Combined	Bragg Creek	Combined	Bragg Creek
500	2,035	1,745	192,700	170,000	420,800	358,000
200	1,215	1,085	146,000	129,000	360,700	312,000
100	820	755	119,000	105,000	321,000	282,000
50	560	525	96,000	85,400	285,700	254,000
20	330	330	73,000	64,900	245,000	221,000
10	205	200	59,700	52,700	238,000	199,000
5	145	140	41,300	37,300	184,000	169,000
2	70	70	21,500	19,700	112,000	103,000

Based on Stantec's analysis of available data, the best estimates of the 2013 flood and the corresponding return periods are provided in Table 12.

Table 12 Best Available Estimates of the 2013 Flood for the Elbow River at Combined and Bragg Creek Stations

	Combined Station		Bragg Creek Station	
Drainage Area	1,200 km^2		791 km^2	
Flood Peak	1,240 m^3/s	210-year	1,150 m^3/s	230-year
7-Day Volume	149,600 dam^3	230-year	138,600 dam^3	250-year

4.4 FLOOD FREQUENCY ESTIMATE AT THE SR1 DIVERSION SITE

The drainage area for the SR1 diversion site is 868 km^2, which is 110% of the drainage area at Bragg Creek and 72% of the drainage area at Glenmore Reservoir. Using linear interpolation of values from Table 11 (excluding the entirely observed datasets at Bragg Creek), the estimated flood frequencies for the Elbow River at the SR1 diversion site are provided in Table 13.

Table 13 Estimated Flood Frequencies for the Elbow River at the SR1 Diversion Site

Return Period (years)	Instantaneous Peak Discharge (m^3/s)	7-Day Volume (dam^3)	56-Day Volume (dam^3)
500	1,800	174,000	371,000
200	1,110	132,000	322,000
100	765	107,000	290,000
50	530	86,600	260,000
20	330	65,600	226,000
10	200	53,100	203,000
5	140	38,100	172,000
2	70	20,000	105,000

5.0 DESIGN APPLICATION

The results of this analysis, in combination with the Probable Maximum Flood Report (under separate cover), will provide the basis for the hydraulic design of the SR1 Project. Preliminary design activities will utilize the values contained herein to update the concept design. Forecasting of operation frequency and duration will follow structure design updates. Finally, operations guidelines will be developed.

The SR1 Project will be designed to mitigate for a flood with a magnitude equal to or less than the 2013 event. Individual project elements may utilize a design basis less than or greater than the 2013 flood magnitude. For instance, the Province may select to design erosion protection within the Diversion Channel using the 25-year event to limit construction costs with the understanding that future maintenance costs may be higher. Similarly, the design of the dam crest elevation and emergency spillway will utilize the Probable Maximum Flood event in accordance with dam safety regulations.

Operations guidelines will be developed using flood hydrographs previously observed in the gauge record and synthetic flood hydrographs developed based on the results of this analysis. Operations scenarios and guidelines will be reported in a separate document.

At the time of document preparation, it is noted that operation of the SR1 Project is anticipated for a flood event with a peak discharge at Glenmore Reservoir of 160 cms which has return period of approximately 7 years.

6.0 REFERENCES

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APPENDIX A

OBSERVED AND ESTIMATED PEAK FLOW AND VOLUME DATA SET TABLES

Prepared for:
Alberta Transportation

Prepared by:
Stantec Consulting Ltd.

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m³/s

Combined Station					
Station Number	Year	Maximum Daily Discharge[1,2]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[3]	Date of Peak Instantaneous Discharge
05BJ001	1908	159	2-Jun	*217.5[4]*	*2-Jun*
05BJ001	1909	94	3-Jun	*120.3[4]*	*3-Jun*
05BJ001	1910	18.6	19-Sep	*19.4[4]*	*19-Sep*
05BJ001	1911	89.5	8-Aug	*113.8[4]*	*8-Aug*
05BJ001	1912	122	16-Jun	*161.1[4]*	*16-Jun*
05BJ001	1913	38.8	10-Aug	*44.5[4]*	*10-Aug*
05BJ001	1914	28.9	18-Jun	*32[4]*	*18-Jun*
05BJ001	1915	239	26-Jun	*379.4*	*26-Jun*
05BJ001	1916	146	29-Jun	*196.5[4]*	*29-Jun*
05BJ001	1917	147	3-Jun	*198.8[4]*	*3-Jun*
05BJ001	1918	35.4	10-Jun	*39.9[4]*	*10-Jun*
05BJ001	1919	72.5	6-Aug	*89.8[4]*	*6-Aug*
05BJ001	1920	67.7	13-Jul	*69.9*	*13-Jul*
05BJ001	1921	37.4	25-May	*42.5[4]*	*25-May*
05BJ001	1922	26.5	17-May	*28.9[4]*	*17-May*
05BJ001	1923	331	1-Jun	*402.1*	*1-Jun*
05BJ001	1924	59.5	4-Aug	*71.9[4]*	*4-Aug*
05BJ001	1925	66.5	12-Jun	*71.6*	*12-Jun*
05BJ001	1926	88.1	11-Sep	*111.6[4]*	*11-Sep*
05BJ001	1927	83.3	10-Jun	*84.7*	*10-Jun*
05BJ001	1928	100	19-Jun	*107.9*	*19-Jun*
05BJ001	1929	382	3-Jun	*433.2*	*3-Jun*
05BJ001	1930	30.6	31-May	*32.3*	*31-May*
05BJ001	1931	22.9	8-Apr	*28.3*	*8-Apr*
05BJ001	1932	311	3-Jun	*713.6*	*3-Jun*
05BJ001	1933	30.9	16-Jun	*42.8*	*16-Jun*

Stantec

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m^3/s

Combined Station					
Station Number	Year	Maximum Daily Discharge[1,2]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[3]	Date of Peak Instantaneous Discharge
05BJ005	1934	24.4	10-Jun	*26.4[4]*	*10-Jun*
05BJ005	1935	29.2	18-Jun	*32.3[4]*	*18-Jun*
05BJ005	1936	32.3	2-Jun	*36.2[4]*	*2-Jun*
05BJ005	1937	53.2	14-Jun	*63.4[4]*	*14-Jun*
05BJ005	1938	60.3	3-Jul	*73.1[4]*	*3-Jul*
05BJ005	1939	90.6	17-Jun	*122.3*	*17-Jun*
05BJ005	1940	36.2	6-Sep	*41.1[4]*	*6-Sep*
05BJ005	1941	39.1	2-Jun	*44.7[4]*	*2-Jun*
05BJ005	1942	127	11-May	*226.5*	*11-May*
05BJ005	1943	31.1	4-Apr	*34.8[4]*	*4-Apr*
05BJ005	1944	23.9	13-Jun	*25.7[4]*	*13-Jun*
05BJ005	1945	74.8	1-Jun	*83.5*	*1-Jun*
05BJ005	1946	50.7	7-Jun	*56.6*	*7-Jun*
05BJ005	1947	68.2	11-May	*78.4*	*11-May*
05BJ005	1948	127	23-May	*259.1*	*23-May*
05BJ005	1949	19.7	22-May	*20.7[4]*	*22-May*
05BJ005	1950	35.1	16-Jun	*38.2*	*16-Jun*
05BJ005	1951	137	31-Aug	*170.8*	*31-Aug*
05BJ005	1952	79	23-Jun	*90.9*	*23-Jun*
05BJ005	1953	132	4-Jun	*166.8*	*4-Jun*
05BJ005	1954	48.1	25-Aug	*56.6[4]*	*25-Aug*
05BJ005	1955	45.9	20-May	*53.5[4]*	*20-May*
05BJ005	1956	37.4	4-Jul	*42.5[4]*	*4-Jul*
05BJ005	1957	30.3	9-Jun	*33.7[4]*	*9-Jun*
05BJ005	1958	54.9	14-Jul	*65.7[4]*	*14-Jul*
05BJ005	1959	49.3	27-Jun	*58[4]*	*27-Jun*

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m^3/s

Combined Station					
Station Number	**Year**	**Maximum Daily Discharge[1,2]**	**Date of Maximum Daily Discharge**	**Peak Instantaneous Discharge[3]**	**Date of Peak Instantaneous Discharge**
05BJ005	1960	30	4-Jun	*33.4*[4]	*4-Jun*
05BJ005	1961	51	27-May	*60.3*[4]	*27-May*
05BJ005	1962	27.8	17-Jun	*30.6*[4]	*17-Jun*
05BJ005	1963	124	30-Jun	*178.7*	*30-Jun*
05BJ005	1964	62.9	9-Jun	*76.5*	*9-Jun*
05BJ005	1965	104	18-Jun	*134.5*	*18-Jun*
05BJ005	1966	36.5	3-Jul	*41.6*	*3-Jul*
05BJ005	1967	199	31-May	*279.2*[4]	*31-May*
05BJ005	1968	51.3	8-Jun	*60.9*[4]	*8-Jun*
05BJ005	1969	125	30-Jun	*165.1*[4]	*30-Jun*
05BJ005	1970	97.1	14-Jun	*124.6*[4]	*14-Jun*
05BJ005	1971	85.2	6-Jun	*107.6*[4]	*6-Jun*
05BJ005	1972	41.9	1-Jun	*48.4*[4]	*1-Jun*
05BJ005	1973	45.3	27-May	*53*[4]	*27-May*
05BJ005	1974	62	18-Jun	*75.3*[4]	*18-Jun*
05BJ005	1975	49	21-Jun	*57.8*[4]	*21-Jun*
05BJ005	1976	37.9	6-Aug	*43.3*[4]	*6-Aug*
05BJ005	1977	16.3	15-Aug	*16.7*[4]	*15-Aug*
05BJ005	1978	*41.1*	6-Jun	*47.3*[4]	*6-Jun*
05BJ010	1979	**36**	27-May	41.3	27-May
05BJ010	1980	**52.9**	4-Jun	59.7	4-Jun
05BJ010	1981	**101**	26-May	121	26-May
05BJ010	1982	**32.3**	16-Jun	38.2	15-Jun
05BJ010	1983	**30.4**	25-Apr	42.8	25-Apr
05BJ010	1984	**20.7**	9-Jun	21.9	9-Jun
05BJ010	1985	**63.2**	13-Sep	71.7	13-Sep

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m^3/s

Combined Station					
Station Number	**Year**	**Maximum Daily Discharge[1,2]**	**Date of Maximum Daily Discharge**	**Peak Instantaneous Discharge[3]**	**Date of Peak Instantaneous Discharge**
05BJ010	1986	**49.7**	29-May	54.1	29-May
05BJ010	1987	**27.4**	20-Jul	29.6	19-Jul
05BJ010	1988	**29.4**	8-Jun	35.1	8-Jun
05BJ010	1989	**22.4**	10-Jun	23	10-Jun
05BJ010	1990	128	26-May	158	26-May
05BJ010	1991	45.6	-	*53*[4]	-
05BJ010	1992	110	15-Jun	122	15-Jun
05BJ010	1993	84.8	17-Jun	*105.5*[4]	-
05BJ010	1994	67	7-Jun	*81.2*[4]	-
05BJ010	1995	**213**	17-Jun	*293*[4]	-
05BJ010	1996	44.3	9-Jun	*51.3*[4]	-
05BJ010	1997	59.8	1-Jun	*71.6*[4]	-
05BJ010	1998	102	28-May	*129.4*[4]	-
05BJ010	1999	54.9	15-Jul	63.4	15-Jul
05BJ010	2000	18.3	11-Jun	19	11-Jun
05BJ010	2001	43.3	5-Jun	*50*[4]	-
05BJ010	2002	80.4	17-Jun	89.0	17-Jun
05BJ010	2003	35.2	26-May	60.1	26-Apr
05BJ010	2004	36.4	26-Aug	*41.3*[4]	-
05BJ010	2005	268	18-Jun	338	18-Jun
05BJ010	2006	122	16-Jun	140	16-Jun
05BJ010	2007	68.9	18-Jun	76.1	7-Jun
05BJ010	2008	183	25-May	220	25-May
05BJ010	2009	40.2	14-Jul	43.6	14-Jul
05BJ010	2010	49.1	18-Jun	51.9	18-Jun
05BJ010	2011	180	27-May	215	27-May

Table A.1 Annual Maximum Daily and Peak Instantaneous Flows at the Combined Station (1908-2013), in m³/s

Combined Station					
Station Number	**Year**	**Maximum Daily Discharge[1,2]**	**Date of Maximum Daily Discharge**	**Peak Instantaneous Discharge[3]**	**Date of Peak Instantaneous Discharge**
05BJ010	2012	110	24-Jun	136	24-Jun
05BJ010	2013	682[5]	21-Jun	1240[6]	21-Jun

[1] **Bolded** maximum daily discharge values were obtained from WSC complete daily hydrographs as WSC did not provide maximum daily discharge values for these years

[2] Underlined maximum daily discharge values were computed using the following relationship derived from observed maximum daily discharge data: $Q_{Combined} = 1.42*Q_{Bragg}^{0.93}$

[3] *Italicized-shaded* annual peak instantaneous discharge, annual maximum daily discharge values and date instantaneous peak dates were taken from '*Alberta Environment 1983. Calgary floodplain study, volume II, Appendix B, Hydrologic Analysis by A. DeBoer*.'

[4] Annual instantaneous peak flows were estimated from annual maximum daily flow based on the following relationship $Q_{instantaneous} = 0.7943*Q_{daily}^{1.1002}$

[5] The 2013 maximum daily discharge was referenced by AMEC (2014) as provided by City of Calgary as a preliminary estimate

[6] The 2013 peak instantaneous discharge is preliminary and was provided by the City of Calgary

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m^3/s

Bragg Creek Station				
Year	Maximum Daily Discharge[1]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[2]	Date of Peak Instantaneous Discharge
1908	158	-	*194*	-
1909	90.1	-	*106*	-
1910	15.8	-	*16.2*	-
1911	85.5	-	*100*	-
1912	119	-	*143*	-
1913	34.9	-	*37.9*	-
1914	25.4	-	*27.0*	-
1915	245	-	*311*	-
1916	145	-	*176*	-
1917	146	-	*177*	-
1918	31.6	-	*34.1*	-
1919	68.2	-	*78.2*	-
1920	63.3	-	*72.3*	-
1921	33.5	-	*36.3*	-
1922	23.1	-	*24.4*	-
1923	348	-	*454*	-
1924	55.2	-	*62.2*	-
1925	62.1	-	*70.8*	-
1926	84.0	-	*98*	-
1927	79.1	-	*92*	-
1928	96.3	-	*114*	-
1929	406	-	*536*	-
1930	27.0	-	*28.8*	-
1931	19.8	-	*20.6*	-
1932	325	-	*422*	-
1933	-	-	-	-
1934	21.2	-	*22.2*	-
1935	23.6	17-Jun	*24.9*	-
1936	27.5	1-Jun	*29.4*	-
1937	64.8	13-Jun	*74.0*	-
1938	77.9	2-Jul	*90*	-

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m³/s

Bragg Creek Station				
Year	Maximum Daily Discharge[1]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[2]	Date of Peak Instantaneous Discharge
1939	74.8	22-Jun	*86.4*	-
1940	21.2	25-May	*22.2*	-
1941	44.5	2-Jun	*49.4*	-
1942	155	11-May	*190*	-
1943	44.2	3-Jul	*49.0*	-
1944	22.9	13-Jun	*24.1*	-
1945	107	26-May	*127*	-
1946	42.5	29-May	*47.0*	-
1947	60.6	10-May	*68.9*	-
1948	183	23-May	*227*	-
1949	17.6	22-May	*18.1*	-
1950	44.2	15-Jun	58.0	15-Jun
1951	82.7	30-Aug	110	30-Aug
1952	59.7	23-Jun	71.4	12-Jun
1953	118	13-Jun	181	13-Jun
1954	39.4	25-Aug	43.9	25-Aug
1955	37.1	12-Jun	47.6	19-May
1956	30.9	21-May	35.4	21-May
1957	28.9	8-Jun	30.0	8-Jun
1958	37.9	13-Jul	40.2	13-Jul
1959	39.9	27-Jun	45.9	27-Jun
1960	28.9	3-Jun	29.4	3-Jun
1961	51.0	27-May	57.2	27-May
1962	26.1	16-Jun	28.9	16-Jun
1963	141	30-Jun	268	29-Jun
1964	89.5	8-Jun	97.4	8-Jun
1965	127	18-Jun	184	18-Jun
1966	30.6	5-Jun	32.3	5-Jun
1967	185	31-May	283	31-May
1968	43.9	8-Jun	50.7	10-Jun
1969	139	29-Jun	170	29-Jun

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m^3/s

Bragg Creek Station				
Year	Maximum Daily Discharge[1]	Date of Maximum Daily Discharge	Peak Instantaneous Discharge[2]	Date of Peak Instantaneous Discharge
1970	92.0	14-Jun	112	14-Jun
1971	89.2	6-Jun	116	6-Jun
1972	49.8	1-Jun	56.1	1-Jun
1973	43.3	26-May	47.0	7-Jun
1974	66.0	17-Jun	170	29-Jun
1975	49.3	20-Jun	53.5	20-Jun
1976	36.0	6-Aug	42.5	6-Aug
1977	15.8	14-Aug	17.1	13-Aug
1978	44.5	6-Jun	49.8	6-Jun
1979	32.1	27-May	38.4	27-May
1980	51.7	3-Jun	69.3	4-Jun
1981	98.2	26-May	123	26-May
1982	28.9	16-Jun	30.7	14-Jun
1983	26.2	30-May	31.5	25-Apr
1984	19.4	12-Jun	21.1	12-Jun
1985	61.2	13-Sep	79.7	13-Sep
1986	48.9	28-May	57.2	28-May
1987	24.3	19-Jul	26.5	19-Jul
1988	28.9	8-Jun	37.3	8-Jun
1989	20.4	9-Jun	23.1	9-Jun
1990	129	26-May	172	26-May
1991	41.4	21-May	47.2	21-Jun
1992	88.7	15-Jun	119	15-Jun
1993	80.4	16-Jun	93	15-Jun
1994	52.1	7-Jun	72.0	7-Jun
1995	190	7-Jun	377	6-Jun
1996	43.5	8-Jun	48.4	9-Jun
1997	47.8	31-May	54.2	1-Jun
1998	103	28-May	141	28-May
1999	48.3	15-Jul	53.7	15-Jul
2000	14.4	10-Jun	15	10-Jun

Table A.2 Annual Maximum Daily and Peak Instantaneous Flows at Bragg Creek Station (1908-2013), in m³/s

Bragg Creek Station				
Year	**Maximum Daily Discharge[1]**	**Date of Maximum Daily Discharge**	**Peak Instantaneous Discharge[2]**	**Date of Peak Instantaneous Discharge**
2001	39.4	5-Jun	45.2	4-Jun
2002	70.2	16-Jun	87.3	17-Jun
2003	30.9	25-May	61.5	25-Apr
2004	31.4	26-Aug	31.9	26-Aug
2005	231	7-Jun	308	7-Jun
2006	75.1	16-Jun	97.9	15-Jun
2007	54.0	7-Jun	83.7	6-Jun
2008	125	24-May	204	24-May
2009	39.4	14-Jul	51.2	13-Jul
2010	43.3	18-Jun	48.4	17-Jun
2011	95.5	27-May	112	27-May
2012	83.2	24-Jun	110	6-Jun
2013	756	-	1150[3]	21-Jun

[1] Underlined maximum daily discharge values were computed using the following relationship derived from observed maximum daily discharge data: $Q_{Bragg} = 0.70*Q_{Combined}^{1.075}$

[2] *Italicized-shaded* peak instantaneous discharge values were computed using the following relationship derived from observed discharge data at Bragg Creek Station: $Q_{inst.} = 0.82*Q_{daily}^{1.11}$

[3] The 2013 peak instantaneous discharge is preliminary and was provided by the City of Calgary

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Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam³

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
1908	77,250	221,737	71,070	201,781
1909	41,930	194,296	38,576	176,810
1910	10,040	56,945	9,237	51,820
1911	30,283	120,355	27,861	109,523
1912	43,865	192,344	40,356	175,033
1913	17,444	96,396	16,049	87,721
1914	15,777	84,378	14,515	76,784
1915	73,129	285,068	67,279	259,412
1916	67,409	315,567	62,017	287,166
1917	55,477	237,635	51,039	216,247
1918	17,893	77,754	16,462	70,756
1919	22,654	65,856	20,842	59,929
1920	28,547	133,160	26,263	121,175
1921	19,958	98,142	18,362	89,309
1922	13,141	82,985	12,090	75,516
1923	85,925	323,715	79,051	294,581
1924	28,236	125,451	25,977	114,160
1925	29,920	113,054	27,527	102,880
1926	34,741	136,495	31,962	124,210
1927	38,336	172,428	35,269	156,910
1928	44,090	194,797	40,563	177,266
1929	93,407	195,359	85,934	177,777
1930	15,828	90,582	14,562	82,429
1931	9,780	45,543	8,998	41,444
1932	93,563	184,395	86,078	167,799
1933	17,522	104,604	16,120	95,190
1934	13,150	64,554	13,902	51,292
1935	15,284	72,567	11,647	62,954
1936	12,900	47,686	8,111	22,262
1937	25,281	91,825	25,168	84,627
1938	26,205	145,990	36,063	169,171
1939	34,059	118,974	36,685	129,954
1940	13,401	69,886	10,161	50,700

Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam^3

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
1941	17,228	53,803	19,440	56,171
1942	42,941	206,963	41,688	225,219
1943	15,042	100,224	24,805	156,851
1944	12,891	62,577	12,053	45,162
1945	34,793	192,067	38,681	215,240
1946	21,997	105,192	19,241	97,133
1947	26,948	142,379	26,594	139,268
1948	49,352	208,423	51,866	198,729
1949	10,670	59,073	8,148	54,754
1950	19,941	96,820	21,574	92,759
1951	52,695	219,862	37,480	206,194
1952	33,013	149,636	27,596	125,159
1953	57,136	243,294	56,022	232,641
1954	23,129	150,440	17,790	119,318
1955	23,976	142,050	18,697	110,367
1956	17,833	105,382	14,532	87,506
1957	15,535	98,289	13,409	82,201
1958	27,864	134,603	19,475	115,551
1959	20,252	105,935	15,803	89,700
1960	14,403	87,937	12,563	74,954
1961	24,296	102,465	24,192	101,628
1962	15,206	83,876	14,265	80,163
1963	36,331	143,104	38,042	130,343
1964	27,328	138,966	28,944	128,632
1965	35,614	181,863	36,478	142,966
1966	19,639	104,043	18,040	94,962
1967	56,670	199,817	62,761	197,994
1968	23,665	107,200	22,360	97,174
1969	56,462	191,454	54,717	163,685
1970	42,664	127,423	36,711	115,085
1971	32,443	117,590	32,702	117,720
1972	21,643	126,999	25,168	133,419
1973	22,559	119,102	22,792	119,794

Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam^3

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
1974	32,988	150,198	33,204	139,890
1975	25,955	91,150	22,265	88,594
1976	20,097	69,463	16,831	65,971
1977	7,313	42,451	7,177	43,756
1978	-	-	20,753	99,084
1979	16,183	76,275	14,515	67,891
1980	23,052	106,936	24,270	110,248
1981	49,507	187,739	45,317	171,124
1982	17,470	91,247	16,209	82,679
1983	14,636	82,227	13,850	75,125
1984	11,699	56,526	11,197	56,260
1985	20,468	66,937	19,388	66,322
1986	25,445	107,490	24,572	99,187
1987	14,515	59,918	13,141	57,581
1988	12,200	52,282	11,388	52,608
1989	12,165	63,361	11,647	62,134
1990	50,138	167,201	48,082	154,198
1991	-	-	23,924	141,368
1992	37,532	126,481	32,460	117,435
1993	34,007	171,858	28,771	158,795
1994	21,419	83,680	15,163	67,727
1995	52,177	211,671	54,009	194,063
1996	21,289	118,765	21,004	114,765
1997	27,708	113,262	21,410	94,527
1998	42,422	229,150	36,556	190,901
1999	24,062	97,468	21,324	96,768
2000	8,726	45,064	7,430	46,122
2001	19,863	74,382	18,075	71,835
2002	39,303	177,396	35,821	166,933
2003	17,107	87,716	15,630	77,805
2004	19,094	95,247	16,278	89,484
2005	78,071	293,820	63,193	213,313
2006	38,007	109,564	24,382	84,704

Table A.3 Annual Maximum 7-Day and 56-Day Volume at the Combined and Bragg Creek Stations, in dam³

Year	7-Day Volume at the Combined Station	56-Day Volume at the Combined Station	7-Day Volume at the Bragg Creek Station[1]	56-Day Volume at the Bragg Creek Station[2]
2007	27,207	125,064	22,006	103,239
2008	55,106	219,128	45,403	185,069
2009	16,183	80,309	16,381	82,788
2010	23,596	100,138	22,499	94,643
2011	54,734	216,985	37,610	175,980
2012	51,382	207,420	36,003	155,403
2013	149,609	-	138,552	-

[1] *Italicized*-shaded 7-day volume values were computed using the following relationship derived from observed volume data at Combined and Bragg Creek Stations: $V_{Bragg7\text{-}day} = 0.9*V_{Combined7\text{-}day}+382.58$

[2] *Italicized*-shaded 56-day volume values were computed using the following relationship derived from observed volume data at Combined and Bragg Creek Stations: $V_{Bragg56\text{-}day} = 0.86*V_{Combined56\text{-}day}+6498.32$